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Flux of light

Development of framework for OER Platform to Support and Guide the Incorporation of Luminescent Materials in the Product Design Field

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‘Light is the physical phenomenon most responsible for our perception of the world, and yet it is an almost negligible fraction of the electromagnetic energy that surrounds us and connects us to all other things in the universe.’

Addington & Schodek, 2005

Acknowledgements

I want to start this message by expressing my deepest gratitude and admiration to my family, friends, and thesis advisors. You all have inspired and helped me to become the person I am today.

The last couple of years have been turbulent, to say the least. Social outbreaks, lookdowns, physical distance, uncertainty were all part of this process. Nonetheless, my support system remained strong, loving, and resilient.

I want to thank my family for teaching me to dream big, packing me up with tools to reach for the stars, but welcoming me with their arms (and bottles of wine) open when I have had to return.

I want to thank my life-long friends for their patient, their unbreakable trust, and their continuous teachings, like, there is always room for improvement, and there is always time to make someone feel loved.

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Finally, I thank my team, Flavia Papile, Andrea Marinelli, and Barbara Del Curto, for their time, corrections, and drive for improvement.

I dedicate this thesis to Matías & Vicente, *por ser las lucecitas que iluman mis días.*

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Abbreviations

AM	Additive Manufacturing
CC	Creative Commons
CES	Cambridge Engineering Selector
CL	Chemiluminescence
DIY Materials	Do-It-Yourself Materials
EL	Electroluminescence
EU	European Union
GUI	Graphical User Interfaces
HCI	Human-Computer Interaction
ICS Materials	Interactive, Connected, Smart Materials
IoT	Internet of Things
LED	Light-Emitting Diode
LSC	Luminescent Solar Concentrator
LSP	Luminescent Solar Power
MDD	Material Driven Design
ML	Mechanoluminescence
MP	Materials Project
MUI	Material User Interface
OER	Open Educational Resources
OLED	Organic Light-Emitting Diode
PDMS	Polydimethylsiloxane
PL	Photoluminescence
PLED	Polymer light-emitting diodes
REE	Rare Earth Elements

REI	Rare Earth Ions
SOUTHAM	South America
SSL	Solid State Lighting
TL	Thermoluminescence
TLSC	Transparent Luminescent Solar Concentrator
TUI	Tangible User Interfaces

Abstract (Italian)

Nell'area del design del prodotto, una branca del sapere dipendente dal tempo e dominata da mezzi funzionali ed edonici, i materiali sono il mezzo di connessione tra i prodotti e gli utenti.
Le onde attuali propongono che i materiali sono il canale di trasmissione dell'informazione, fornendo un'esperienza definita nel ricevitore quando sono formulati correttamente attraverso le loro proprietà tecniche e sensoriali.

L'introduzione di nuove categorie dirompenti come i materiali dinamici, capaci di impegnarsi in un dialogo sensoriale rispondendo a uno stimolo energetico, ha aperto la necessità di impartire nuovi metodi che guidino la comprensione del loro funzionamento, fabbricazione, impatto e selezione sul campo.

Rispondendo al contesto, questa tesi focalizza l'attenzione su una particolare tipologia presente nel nostro ambiente quotidiano che si distingue per la crescita esponenziale e la varietà di applicazioni che permette, i materiali luminescenti. Nel quadro di guidare e sostenere l'ulteriore incorporazione di questi sistemi di materiali, l'obiettivo principale di questo studio è quello di sviluppare un quadro per uno strumento OER sotto mezzo di interazione dei materiali luminescenti come fonte di ispirazione e di informazione per i colleghi studenti e i pionieri.

La struttura della tesi comprende la revisione della letteratura sulle metodologie di progettazione dei prodotti, sui materiali intelligenti e luminescenti e sui metodi di selezione dei materiali, seguono 16 casi di studio di progetti luminescenti.
Inoltre, presenta il feedback di 30 utenti specifici interrogati per capire le esigenze del mercato rispetto all'argomento, così come un'analisi di quattro banche dati di materiali ben consolidati utilizzati nel campo.

Il risultato organizza un insieme di proprietà e parametri per il caratterizzazione dei materiali luminescenti rispondendo come un metodo decisionale che promuove la conoscenza guidata dall'esperienza per la loro selezione, sotto il nome di Flux of light.

Parole chiave: *Materiali luminescenti, esperienza, proprietà dei materiali, materiali intelligenti, selezione dei materiali.*

Abstract (English)

Within the subject of product design, a time-dependant branch of knowledge dominated by both functional and hedonic means, materials are the connecting medium for products and users.
Current waves pose that materials are the channel to convey information, providing a defined experience in the receiver when formulated properly through their technical and sensorial properties.

The introduction of new disrupting categories such as dynamic materials, able to engage in sensorial dialogue by responding to an energetic stimulus, has opened the need to impart new methods that guide the comprehension of their functioning, fabrication, impact, and selection in the field.

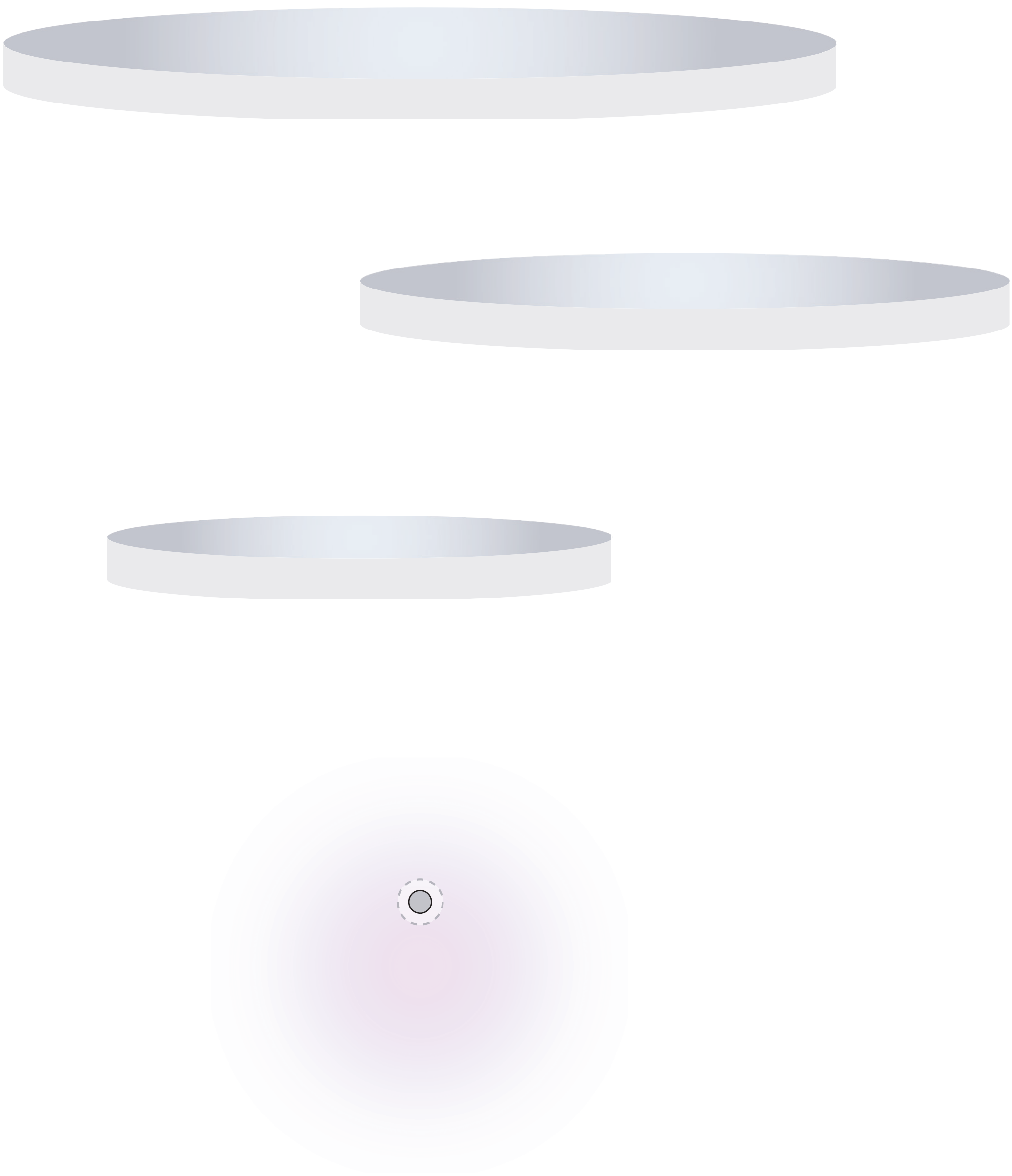
Responding to the context, this thesis centers the attention on one particular kind present in our everyday surroundings that stands out due to exponential growth and the variety of applications it allows, Luminescent materials. Under the scope of guiding and supporting further incorporation of these material systems, the main objective of this study is to develop a framework for an open educational resources (OER) tool under interaction means of luminescent materials as a source of inspiration and information for fellow students and early practitioners.

The thesis structure comprehends the literature review of product design methodologies, smart and luminescent materials, and materials selection methods, followed by 16 case studies of luminescent projects.
Furthermore, it introduces the feedback of 30 questioned targeted users to understand the market's needs regarding the topic, as well as an analysis of four well-established material databases used in the field.

The outcome organizes a set of properties and parameters for the characterization of Luminescent materials responding as a decision-making method that promotes experienced-led knowledge for their selection under the name of Flux of light.

Keywords: *Luminescent materials, experience, materials properties, smart materials, material selection.*

Introduction



Introduction

The field of product design stands out as a discipline that brings together multiple skills, dealing with the challenge of recognizing, merging, and translating information between several areas since its inception. In that sea of variables, a fundamental matter is the core element of any physical object, materials.

Design, as well as materials, are both time-dependent disciplines, affected by the array of the era. The current period, governed by technology advances, interconnection, and exploited communication, has impacted the overall perspective of how products are designed and evaluated.
Advances in synthesis and manufacturing methods have allowed material categories to branch out, while proposals fostered in previous years have taken strength, posing materials as the means to carry not only the product's shape and function but also desired emotional values, making their selection critical for the outcome experience.

In this intersection between design, materials, and technology it is possible to find a particular kind of materials able to respond to interaction in the form of light, know as Luminescent materials.
Recognized for their ability to dynamically transmute in response to an energetic input, these materials have revolutionized the industries of electronics, healthcare, and energy among others due to their compact, cost-effective, efficient results.

Despite their positive evaluation and relevant presence in our everyday surroundings (i.e., screens, luminaires, toys, etc.) Luminescent materials knowledge remains in its infancy in the product design field, With several uncleared links to approach and incorporate them into projects under the parameters of the digital era.
This opportunity guides the thesis objective to support and expand luminescent materials understanding for both students and early practitioners of the design field, aiming to facilitate their exploration and selection.

Recognizing the repercussion of the 2020-2021 pandemic as a digital accelerator, placing online communication tools at the center of needs, it's that the outcome of this thesis will be provided as a mockup of an OER online platform.

Following the phases proposed by the double diamond model, the thesis path covers sections of Discover, Define, Develop, and Deliver.

Emphasis is provided in the first phase due to the complexity of topics to combine and cover while reinforcing the importance of resource recognition and contextual understanding as key variables for any project development. Disseminated into three layers:

> **Nexus layer.** Describes the connection between design and materials, showing the evolution of their link and associated parameters in the product design field. Highlights the properties evaluated in today's digital era that affect material selection. This preliminary research is conducted by literature review.
>
> **Material layer.** Illustrates materials categorization and classifications to provide contextualization, explaining the difference of each kind. The focuss is then provided to Luminescent materials, understanding their working principle, types, forms, as well as impacts these have had in the field. It finalizes by recognizing their potentialities in

the product design field. The layer is carried based on a literature review, consolidated by analysis sustained on 16 luminescent projects retrieved from different types and industries.

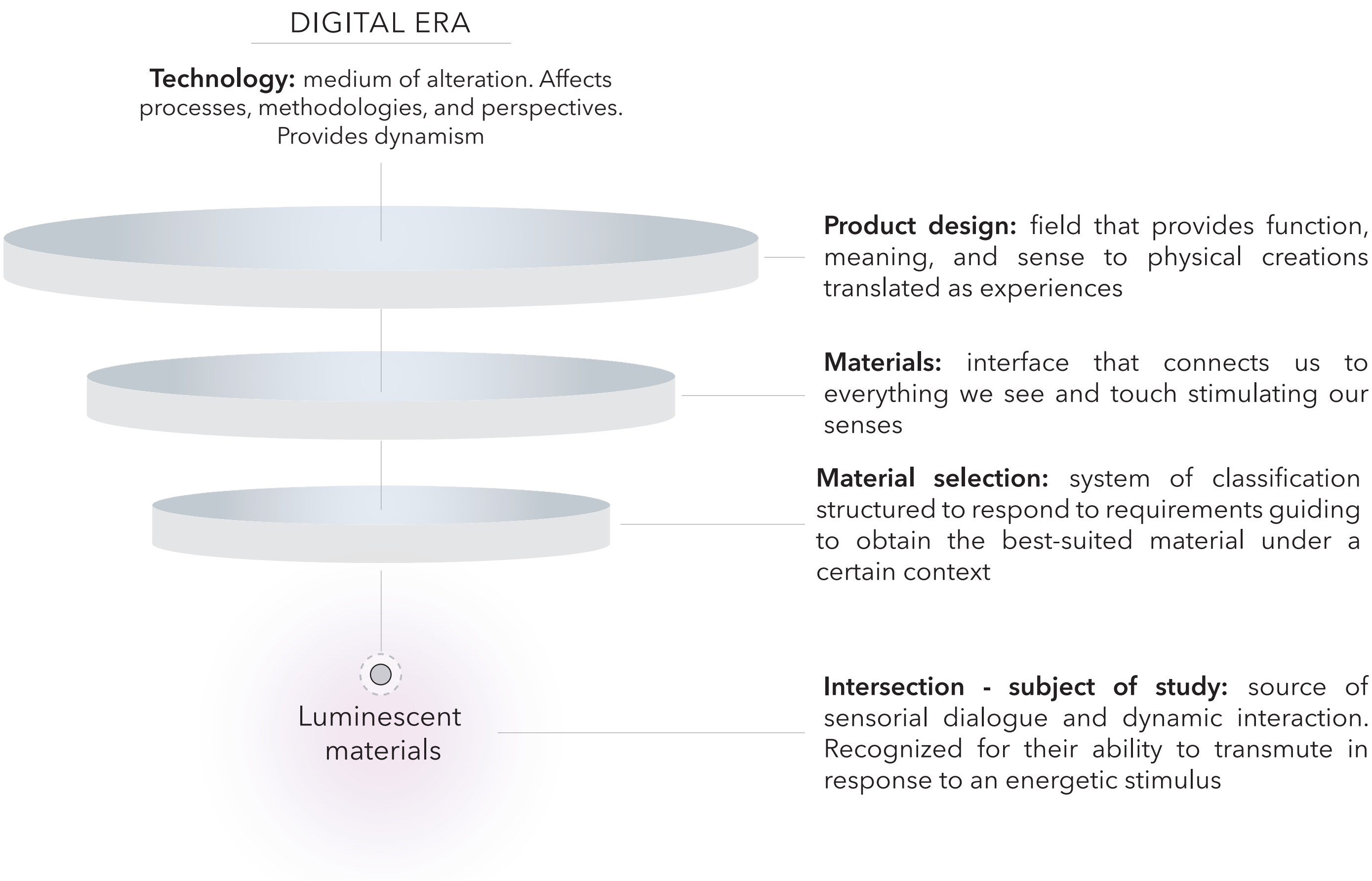
Immaterial layer. Breakdown of variables and methodologies considered for the selection process of a material. From macro to micro, the chapter presents general considerations and structures the platform should consider to reply to the requests of the era. It works its way down until analyzing the market offerings of current online platforms that incorporate or recognize dynamic materials.

The second phase declares the research questions, objectives and methodology followed. Continued by comparing the market offerings and desires of online OER platforms that include or could include luminescent materials. The section finalizes establishing content observations, providing the base and guidelines for the platform to be build up. In detail, the study comprehends literature review, visual comparisons, and user insights.

In the third phase, the platform and its framework build upon the knowledge and information gathered from the previous activities.

The Deliver phase presents the result of the study, a digital platform aiming to support and guide design students and early practitioners in the exploration and incorporation of Luminescent Materials into their projects, opening up new opportunities for (future) creations. The findings, contributions, and limitations of this thesis are discussed in a concluding chapter.

The topics to cover through this thesis are illustrated below.



Chapter 1:

Design and Materials

'This is a time of change, and change is what design should be all about.'

Loy, 2019

1. Design and Materials

Design is a discipline that tends to create ambiguity in its definition due to the lack of established limits or boundaries within itself.
It shares purpose from both art and science, where art is emotional, sensorial, and qualitative; the reaction of an individual to an input of stimulus, dependant on the time and culture of the subject. Sciences, on the other hand, can be recognized as an output of quantitative data, empiric, agreed on by a large number of the population, considered static for long periods, and equal in different cultures.

In the search to create a common ground for designers, models with systematic phases, or steps have been developed, e.g., in product design, the most general sequence is (1) concept creation, (2) embodiment design, and (3) detailed design (Ashby, 2005; Pahl & Beitz, 1996) as seen in Figure 1.
The sequences structure paths to conceptualize and evaluate ideas, translating them into functions, forms, and materials (Hubka & Eder, 1992; Pahl & Beitz, 1996; Roozenburg & Eekels, 1995).

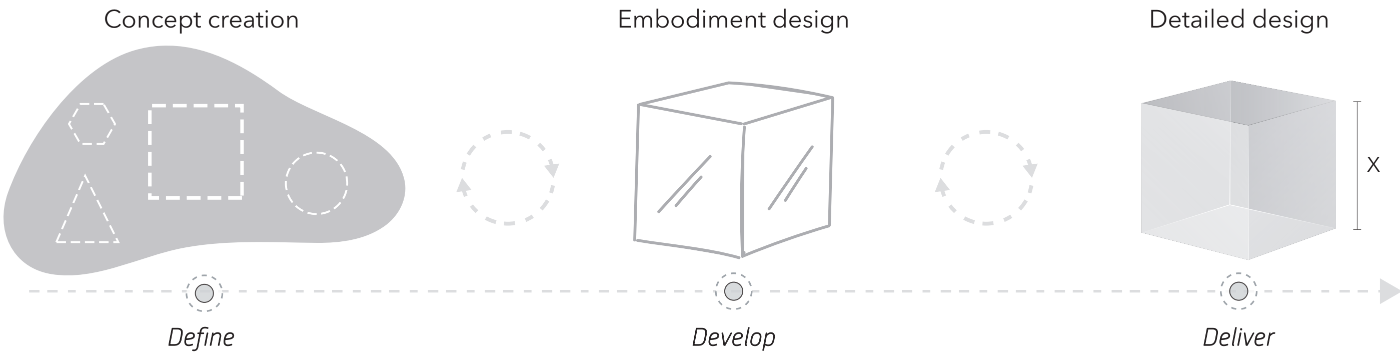


Figure 1. Product design general sequence

As of today, the complexity of projects is changing the paradigm, and socio-cultural context plays an important role, as an iterative variable that is always changing (Dorst, 2019).

Adaptability in design is crucial.

Thankfully the ability of the discipline to mold itself allows it to work as a multidisciplinary link, enabling it to be a **balance between emotional and physical characteristics in function of time.** The summation of objective and subjective data in a determined context.

> *'Designers can work transversally with other disciplines collaborating in their will to understand the complexity of a problem to tackle. Designers are now open to biology, chemistry, medicine, math. Not as a person to confront Humanities and Science but a bridge to connect them.'*
> *Rognoli & García, 2019*

Then, innovation in the field considers **awareness of the available technical knowledge, the industrial context, and the targeted cultures altogether,** providing objects or services that are thinkable, feasible, and accepted by the population (Lefebvre et al. 2014). Nowadays, design becomes also a matter of using the right language creating dialogue about functionality, the intended use of the object, and to generate thoughts and meanings in the user's mind (Redstrom, 2006).

'What matters is the process of finding solutions that are meaningful to people, that enable new experiences and inspire and create a positive impact on society and our own daily lives.'
Ashby & Johnson, 2010

The previous statements allow us to elaborate on our **interpretation of the path of design.**

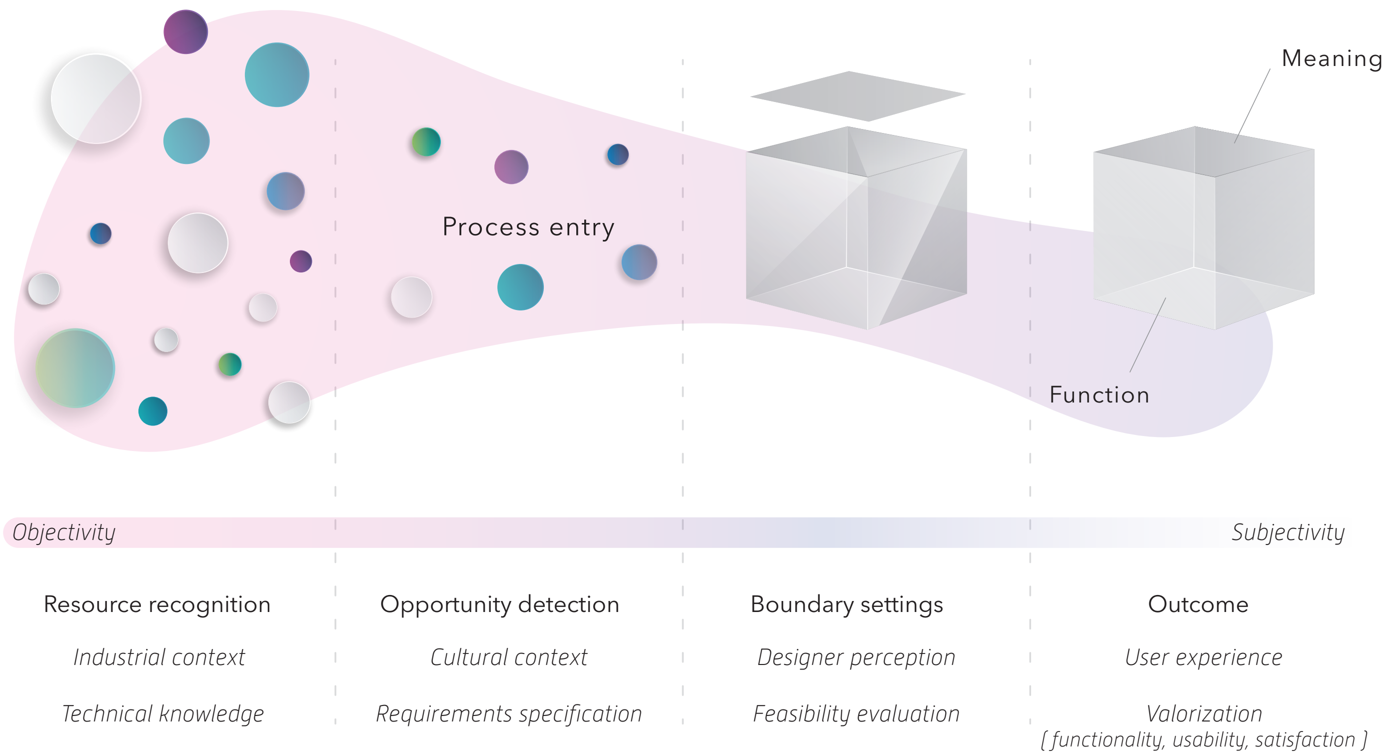


Figure 2. Interpretation of the path of design

At the start point, there is **recognition of the available resources** (e.g., technology, knowledge, materials, processes) **related to the period and location**.
Posteriorly, a **scan of the scenario** is carried, analyzing opportunities, establishing the objectives, and the targeted stakeholders of the project. During this step, it is relevant to recognize the **requirements according to the socio-cultural context** (i.e., constraints). Possible **solutions are iterated** under the designer's subjectivity, tested to verify the feasibility and acceptance of proposals, helping to select the best fit.
At the final stage, an **outcome is delivered**. Its goal is to provide an **experience**, composed of a dialogue that will be both objective (i.e., it serves its purpose, functional outcome agreed on by many people) and subjective (interpretation of meaning, satisfaction, perceived by the user due to his/her context and background).

As the process nears a result, the outcome becomes more subjective due to interaction. Each interaction is an individual dialogue between object-user.
Understanding the variables that affect these interactions is the key to fabricate a desire experience.

In the case of tangible outcomes, as in product design, the interaction occurs through the products' surface.

'The surface refers to the outermost or topmost part of the product. Therefore, the product surface differs depending on the material constituting the surface, and the surface stimulus varies depending on the characteristics of the material'
Kim et al. 2017

If the product designer does not consider the product's surface properly, the user may not adopt the product at all. This is why, **materials are the merging point between products and people** and will play a fundamental role in the user experience, **that comprehends both function and meaning.**

1.1 Approaching Materials

'It is materials that give substance to everything we see and touch.'
Ashby & Johnson, 2010

There are two axioms presented by Karana (2009) that will be taken as a base ground for the development of this thesis:

- *'All living things and lifeless things around us share one property in common: materials.'*

- *'Materials do not have meanings unless we interact with them in a particular context.'*

By definition[1], materials are made of matter, that is the '*substance that occupies space, has mass, and is composed predominantly of atoms consisting of protons, neutrons, and electrons, that constitutes the observable universe, and that is interconvertible with energy*'. Meaning, **matter is, as everything that surrounds us, affected by energy.**

The **selection of every material is inherently dominated by its interaction with some type of energy stimulus**, and an energy stimulus is the result of difference. Whenever an entity changes, energy flows and transfer itself from one place to another, this can or cannot include a **change of form**. Energy can only be quantified and measured as it moves or by its potential to move, and for energy to flow, there must be a difference from the energy that can flow (i.e., potential energy) to the energy that is flowing (i.e., kinetic energy).

Listed below there are types of energy differences, as defined by Addington et al. (2005):

- Heat: driven by a temperature difference
- Work: driven by a pressure difference
- Potential: driven by a height difference
- Electrical: driven by charge difference
- Kinetic: driven by momentum difference
- Elastic: driven by deflection difference
- Chemical: driven by atomic attraction differences
- Nuclear: driven by quanta differences
- Magnetic: driven by moving charge differences

All of the previous energy stimulus when acting with matter, are governed by the laws of thermodynamics, whether it is the appearance of an object in light or the expansion of a material with heat (Addington et al. 2005). Moreover, **all matter reactions to energy difference in a specific context** (then no longer recognized as matter, now as material) **are mediated by the properties of that particular material.**

Material properties are a brick in this thesis, making it important to share meaning of them. Properties comprehend a broad amount of information, the word itself can be defined as an attribute, quality or characteristic of something (Oxford Languages Definition, 2020).

'All attributes, qualities, and characteristics of a material can be described as material properties.'
Höelter, 2019

1 Definitions cited from Merriam-Webster. Available at www.merriam-webster.com (Accessed: May 27, 2020)

Today, several material classifications have been proposed to group them according to their characteristics or attributes, these classifications depend on a selected drive, but all look up to highlight the properties that point to the usage behavior of materials according to that drive. The most conventional classification is by grouping materials into six broad families according to their application or appearance. For example, Ashby et al. (2010) propose the families of **ceramics, glasses, metals, polymers & hybrids. These families correspond to a category also known as Inactive Materials,** to be discussed in the next chapter.
Regardless of the system used, they are all based on the essential determinants of materials, **their composition**.

The composition of the material, meaning their internal structure (crystalline, amorphous, or polycrystalline) and the bonding forces between them (ionic, covalent, metallic, and Van der Waals for molecules bonding) are the initial point to understand intrinsic and extrinsic properties, the most general groups of material properties. Intrinsic properties correspond to something that is entirely about that thing (eg. density); whereas extrinsic properties are not entirely about that thing (eg. weight) (Weatherson & Marshall, 2002).

The concepts discussed in this section have been resumed graphically in Figure 3.

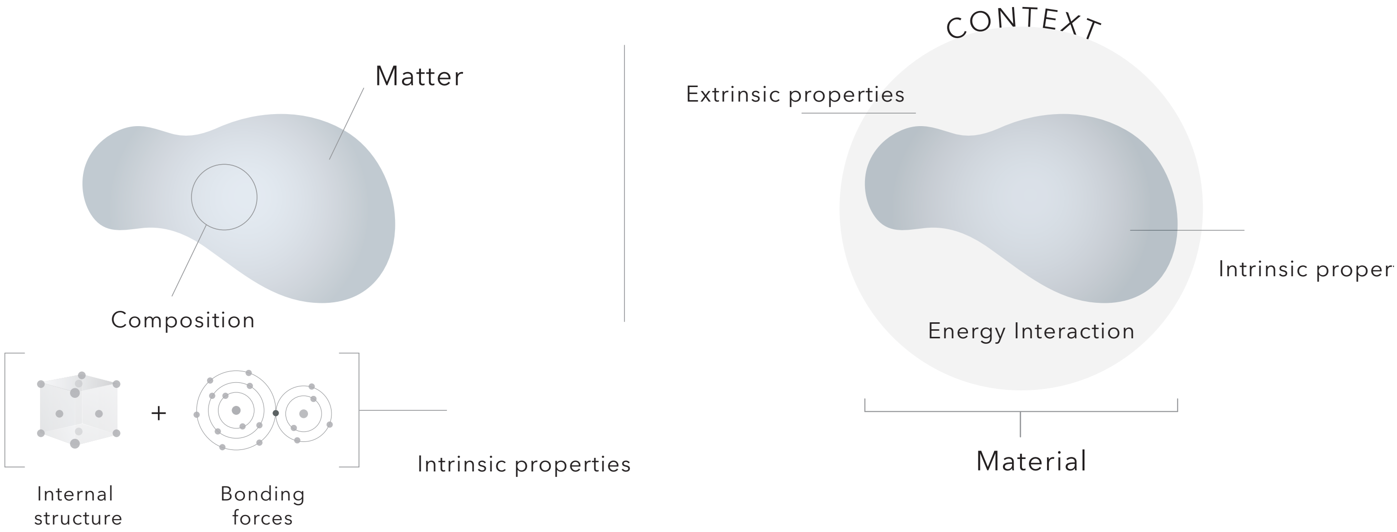


Figure 3. From matter to material

The variables of composition, energy interaction, and context are the reason for differences in the performance of various materials, corresponding partly to why, in certain applications or environments, a material is selected over another.

In the case of product interaction, materials properties, together with the material performance in the defined scenario will impact the dialogue between product and user, affecting the person's perception, playing a key role as the main messenger for the product - person communication.

The topics of material properties, materials classifications, and energetic stimulus will be revisited in sections 1.3.1, 2.1., 2.2

1.2 A timeline path: the evolution of materials in product design

'Matter becomes material when it is included in a design project and becomes part of the product.'
Manzini, 1986

Product design emerged as a profession during the eighteenth century in response to mass production and the design challenges it created. It is a discipline linked to large-scale manufacturing and distribution, responsible for shaping our physical world considering economic manufacturing drivers, such as standardization and repeatability (Loy, 2019). Nowadays, the product's in our surroundings derived primarily from industrial materials, i.e., materials that answer to mass production requirements and constraints (Garcia & Rognoli, 2019).

Design and its subcategory, product design, are subjects of change. **Products are created to satisfy human needs, which are highly time dependant.** Consequently, the discipline is and must be constantly evolving to maintain relevance in the era.

At the start of the XX century, the Bauhaus school promoted geometrical and abstract forms designed to answer to the new needs of people and industrialized society. In this period, design became not only a matter of giving shape to objects, but it was also focused on ways of use and living (Bergamaschi, 2010).
Mankind's history of products is bonded to the history of materials and their processes (Karana, 2009). Materials are a key factor in the improvement of design. The result of these two is the embodiment of new forms for new products commanded according to the period needs. Materials can boost a product's value, contributing to meanings, and experiences.

In the era of mass-production designers were frequently locked into the contradictory practice of trying to design the best possible outcomes yet encourage obsolescence for repeat sales, fortunately, the social and environmental impacts of mass production began to be understood towards the end of the twentieth century (Loy, 2019). At the beginning of the XXI century, ideas as the ones plasmated by Tatum (2004) *'every design decision, however small, has consequences because of the cumulative effects of incremental change'*, took strength and are part of the current vision of design.

Now, entering a new **era of digital technology, where boundaries between the physical and digital are blurring in all areas**, thanks to the field of Human-Computer Interaction (HCI) and its immaterial digital pillars IoT, AI and Big Data, digital fabrication technologies, such as additive manufacturing (AM), prove that the demand for product designers to standardize manufacturing and develop one-size-fits-all products are being removed (Hu, 2013; Tseng et al. 2010).

AM simplifies the process versus subtractive manufacturing, minimizing or even eliminating the creation of molds and tooling, leading to a **shift from mass-production to mass-personalization.** This is only one example of the vast that exists where it has been plasmated that materials, processes/technologies together with surface finishes are nowadays considered an open playground for designers, enabling and enriching language that explodes and creates new **sensorial experiences**.

We observe a growing ecological orientation in design research, related to the change in consumption of society, impulsed, and impulsing circular economy. Accordingly, how we perceive and experience **an artifact is not just a property of the straight physicality it presents, it is also implicated in personal and social life** (Jung & Stolterman, 2012).

The changes we have witnessed present materials as a source beyond physical or engineering properties. This new role is somewhat invisible, objects are no longer selected for purely functional purposes; **there is an interest in an emotional level that can be achieved through the selected materia**l (Lefteri, 2007).

1.2.1 Digital revolution and education

Proper selection of material allows a designer to define up ahead product feasibility and expected in-user product experience.
One of the aims of this thesis is to provide **recirculation of the information acquired**, for which it is important to comprehend some of the aspects that define the present communication systems, focusing on education.

With the arrival of the **digital era** and its **immaterial layer, characterized as intangible, dynamic, and consisting of virtual and digital information** (Bergamaschi et al. 2016), we have witnessed transformation in worldwide connectivity and communication.
Accelerating every possible process, this era enables knowledge to travel faster than ever before, changing learning and teaching for all disciplines. **The democratization of technology**, together with associated movements such as Creative Commons[2] (CC), and Open Educational Resources[3] (OER) show how **the era is strongly shifting in pedagogy, by transitioning from transmissive education (teacher-centric learning) to transformative education (critical learning).**
Several free platforms grow in variety and information every year that passes by. Some examples of recognized collaborative platforms are Google, Wikipedia, and Youtube, as shown in Figure 4, and described in the webpage www.creativecommons.org.

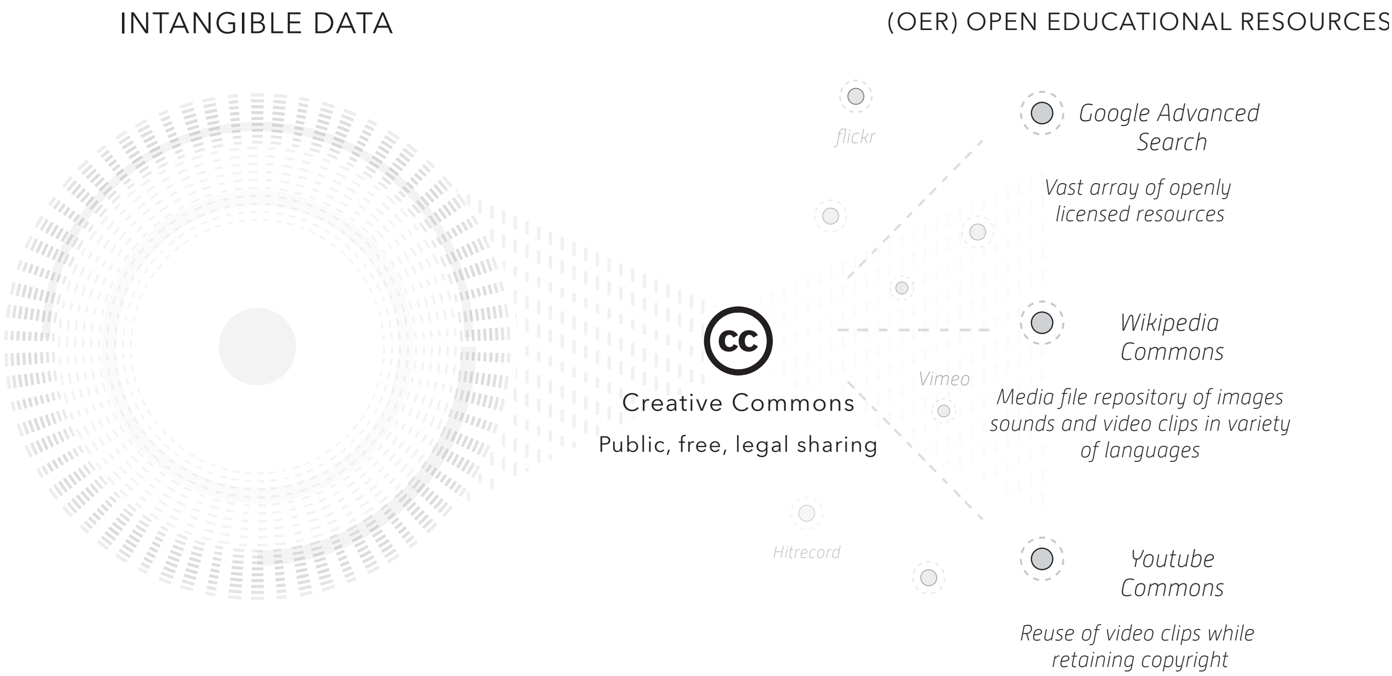


Figure 4. Examples of OER platforms

The introduction of this digital approach comprises two iterative constant cycles (Loy et al. 2019), the first one being the **questioning of knowledge**, opportunities, together with implications of decisions, directly related to the ideas expressed by Tatum (see section 1.2) looking to mature from previous eras mistakes.
The second one is related to a rational selection of areas the subject has chosen to nourish, conditioned by regular updates, a consequence of the 'refresh' characteristic of the period.

2 Defined as 'organization that helps overcome legal obstacles to the sharing of knowledge and creativity to address the world's pressing challenges.' in www.creativecommons.org (Accessed: May 30, 2020).
3 Defined as 'teaching, learning and research materials in any medium – digital or otherwise – that reside in the public domain or have been released under an open license that permits no-cost access, use, adaptation and redistribution by others with no or limited restrictions.' in www.en.unesco.org (Accessed: May 30, 2020).

For this second cycle, **critical selection and management of knowledge acquisition are primordial**, due to the infinite online information branched out to all areas, all technologies, all software, in perpetual actualization.

Evidenced by the COVID - 19 crisis of 2020-2021, the transmission of knowledge and the actors involved must prepare to step up and shift from traditional to virtual. There is a need for guides that help fill gaps between disciplines through tools, and methodologies that encourage communication. It is time to take advantage of the available resources to generate rational useful behavior in the short term, while stimulating questioning, fostering change for the long term.

Contextualizing, Figure 5 places historical milestones that collaborated for the material centered transition we are facing today in product design.

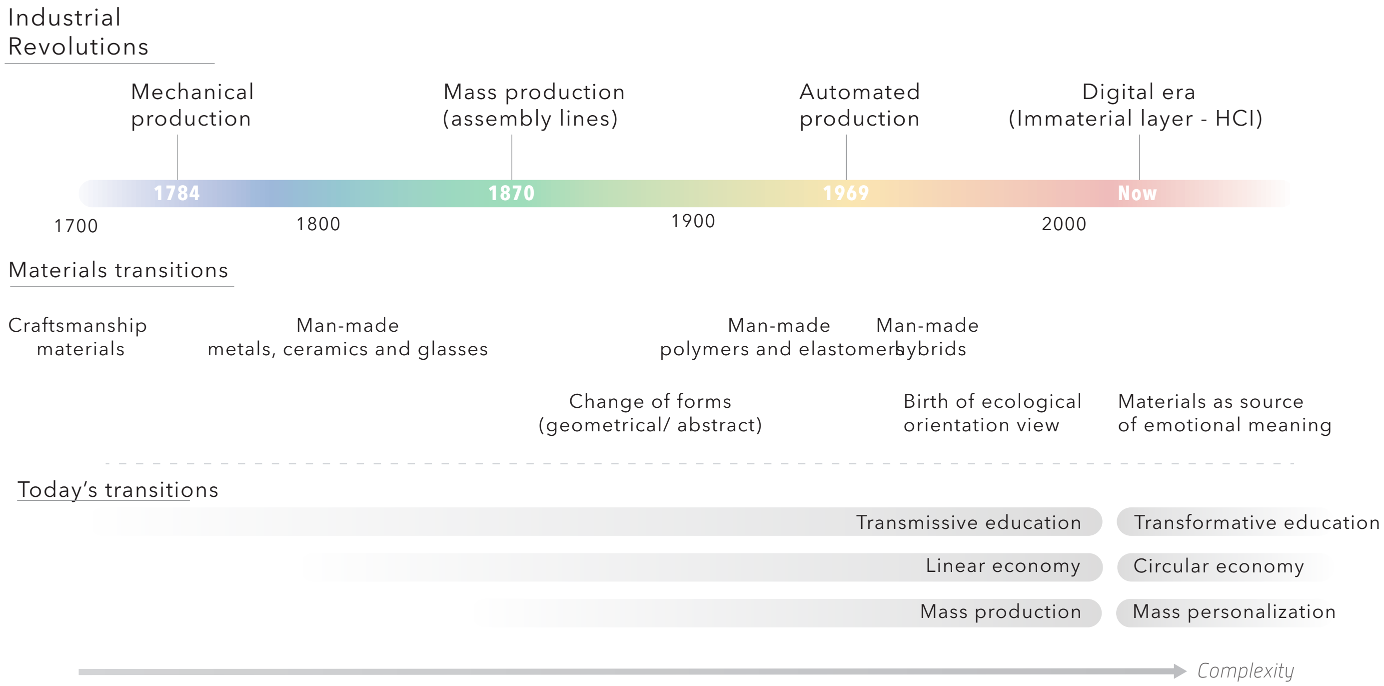


Image information retrieved from:
Ashby, M. F., Shercliff, H., & Cebon, D. (2010). Materials: engineering, science, processing and design. (Figure 1.1)
Hu, S. J. (2013). Evolving Paradigms of Manufacturing: From Mass Production to Mass Customization and Personalization.
Lefteri, C. (2007). Materials: the big attraction and why material innovation is important.
Loy, J., & Novak, J. I. (2019). The Future of Product Design Education Industry 4.0.

Figure 5. Historical events and transitions in the material, productive, educational, and economical world

It is possible to observe there are direct repercussions from technology advances, onto materials perceptions, affecting product experiences. The wave affects all the systems that establish our daily lives.

1.3 Communication in tangible products

The evolution of technology has implied an opening for product design opportunities. Experimentation of material shaping, color, size, weight, has impacted the communication and interaction between products and people.

Materials change their meaning according to the product, and up to date, there isn't an equation that allows us to approach or understand the meaning-material relationship. But **the way products are perceived is articulated by the language designers have conveyed into them.**

Indeed, materials are shaped into products, and it is during this embodiment of matter that the core for its appearance occurs, integrating elements of **form, function, and fabrication,** also known as the **products' formal aspects** (Karana, 2009).
Furthermore, together with the ecological orientation point of view of the digital era, there is a recognition that today's products create reactions through the **emotional impact** they generate in the user (Desmet, 2002). These reactions are caused by the formal aspects the product presents and mediated by the three levels of product experience: **sensorial, emotional, and meaning** (Desmet et al. 2007), according to the context of display.

Desmet (2002) has described emotional impact as:
'the emotion is elicited by meanings derived from the in-store- display, brand, previous experiences, etcetera. It is the combination of all these emotional stimuli that determines what a person experiences towards products.'

Combining both, formal aspects and emotional impact, it is possible to see that the product can transmit two different kinds of messages (Colombo, 2016):

> **Intrinsic information,** which refers to the product mode of use, its functionality, and its character.
>
> **Extrinsic information,** which refers to situations or phenomena that are external to the product itself, and that refers to events that transform over time.

With a clearer spectrum of variables to consider when we talk about product interaction and the result of it, experience, we also acquire a fairer possibility to cover its stages and to achieve product **functionality, usability, and satisfaction, variables that determine the product's value** (Ashby & Jhonson, 2003).

Graphical interpretations of product interaction and product experience are illustrated in Figure 6.

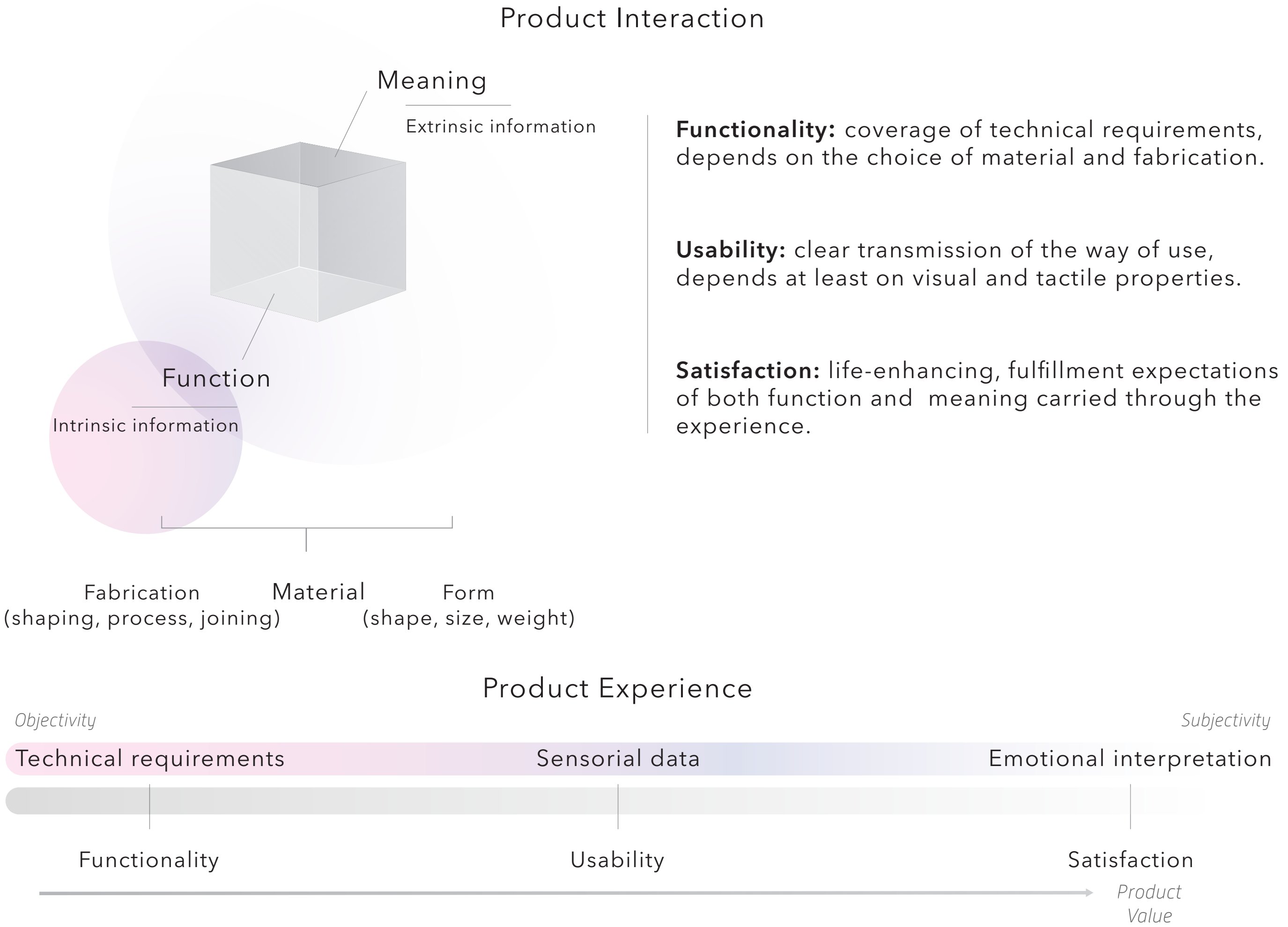


Image based on:
Ashby, M., & Johnson, K. (2010). Materials and Design. In Materials and Design.
Complemented with personal insight.

Figure 6. General variables for product interaction and product experience

As depicted in the image, **the interaction is highly dependant on the context in which it occurs. The more defined the outcome experience is, the better the interaction will be.**

With a general background of how materials impact our surroundings, the importance of their understanding, and the awareness that they reply simultaneously in technical and experiential ways, it is possible to approach the characteristics that enable their selection, their **properties.**

1.3.1 Materials' properties

Materials' properties correspond to the encapsulated data in the Intrinsic/Extrinsic information of a product and **needs to be considered to evaluate the suitability of a material for a defined context, a process also known as material selection,** further discussed in Chapter 3.

Then, materials' properties are what limits the performance of a product to the requirements, scenario, and user-defined, stated in the opportunity detection stage.

The current proposal of the digital era affirms that **material properties present two different levels, the technical and the hedonic** (Hassenzahl, 2003; Pedgley, 2013).
The technical level influences how the material will perform, while at the hedonic level materials are recognized by Höelter (2019) as:
'the substance through which designers can realize their ideas, embody their intentions, produce a desired, and allow products to convey different emotions to users.'

At the technical level, **technical properties** can be found. These are **described through standardized material testing, evaluations of the material under conditions of e.g. compression, tension, flexure. Easily quantified, agreed on, and acknowledged by the population, for which they are also known as 'objective properties'.**
Technical properties comprehend several subcategories, here presented are the ones defined by Ashby et al. (2010):

- physical properties
- mechanical properties
- functional properties
    - chemical properties
    - electrical properties
    - thermal properties
    - optical properties
- environmental properties
- processing properties

Up to now, these have been the base for material selection due to their reliability, their acceptance in the scientific-engineering disciplines, and their accessibility (i.e. several books, platforms, and database present a wide spectrum of materials technical properties).

On the other side, the **hedonic level understands the properties that can be perceived by humans via sensory organs (includes visual, tactile, acoustic, olfactory modalities) and can evoke physiological and psychological responses, know as Sensorial properties** (Akın & Pedgley, 2016).
An example of sensorial properties as defined by Camera & Karana (2018) & Ashby et al. (2010) as:

- tactile properties:
    - roughness
    - hardness
    - temperature perceived

In the case of sensorial properties, these have subjective-objective dual attributes. The objective side refers to the content (e.g., lavender smell) while the subjective side refers to the interpretation created by the person who experiences it (e.g. relaxation to lavender smell).

Therefore, sensorial properties are dependant on user characteristics, product context, and environmental conditions (Zuo, 2010).

In some cases, the objective aspect of sensorial properties can be defined by the summation of multiple technical properties, for instance, the softness of material could be defined on the materials Young's Modulus (the ability to stretch elastically) its hardness (the resistance to indentation and scratching) and the Surface Roughness (the measure of the fine irregularities on a surface) (Höelter, 2019).
The subjective aspects of sensorial properties, comprehending **emotions, associations, values conveyed by the material, are encompassed by intangible properties** (Karana, 2009; Piselli, 2018) which are **determined by the socio-cultural background and context of the user,** a dynamic mean.

Together, both subjective/objective aspects of material sensorial properties affect how users interact with the respective product, and in the whole situational context, construct an individual **material experience** (Giaccardi et al. 2015, Karana et al. 2013).

Combining both levels, technical and hedonic, it is possible to articulate a property profile.
The material property profile defines the interaction and comprehends aspects such as ergonomics and aesthetics.

Subjected to the era, the properties profile is a dynamic source of data that depends on the resources with and on which it has been tested.

This ideation is depicted in Figure 7.

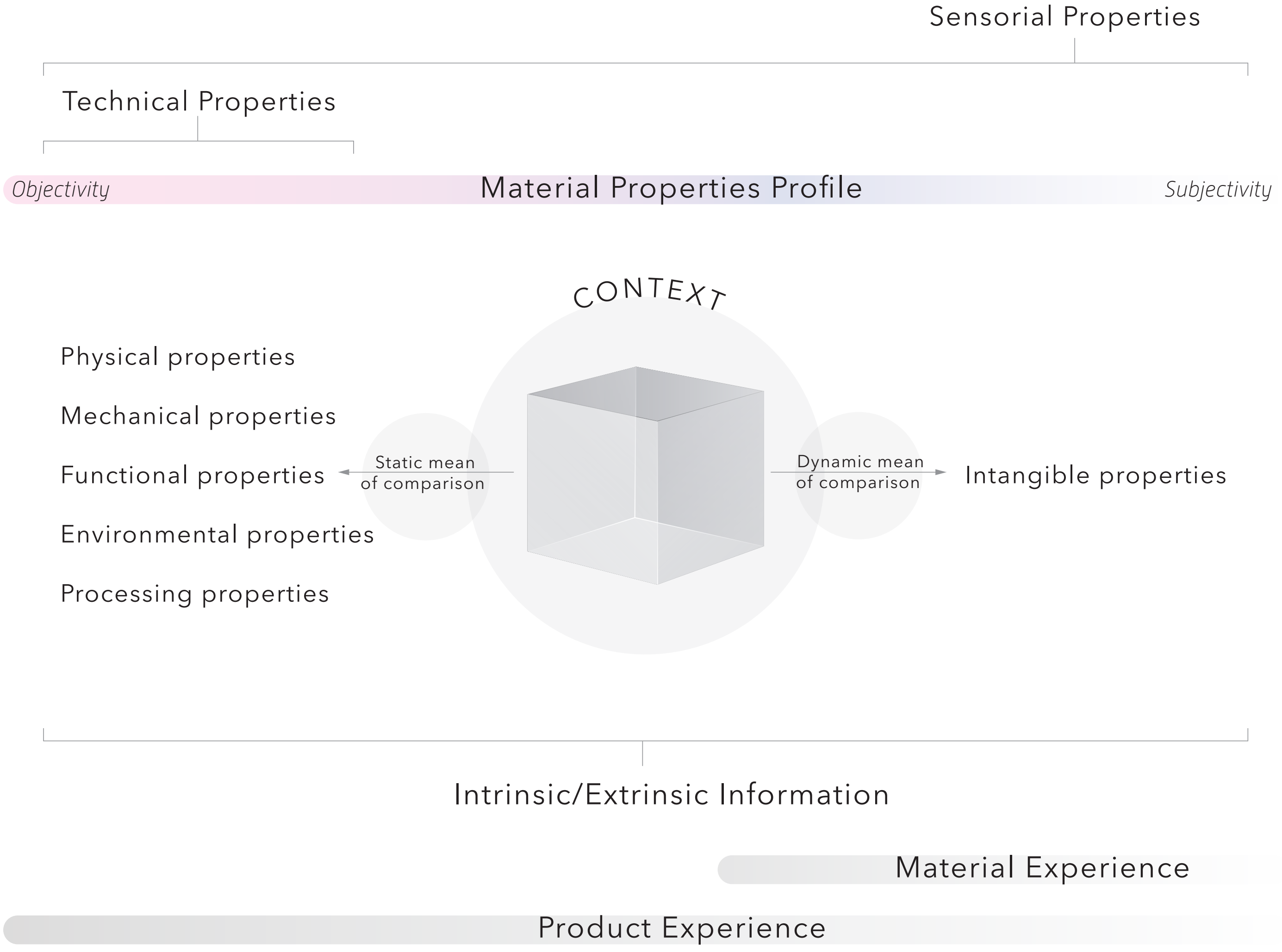


Figure 7. Properties - base for materials property profile

As observed, familiarization with technical properties definition is common, and by summation, general understanding of the objective aspect of sensorial properties can be achieved.
The situation gets wicked regarding properties that would seem to have a more abstract background, as is the case of Intangible ones.

Aware that the impact of user context and background can play on the material interpretation is that the next section pretends to elaborate on such topics, as a bridge to fully comprehended the material profile.

1.3.2 Material experience

Materials owe their expressiveness and their wealth of quality as well as their significance to the fact that they **are sensitive matter, stimulating the perception and interpretation** (Rognoli, 2010).

As stated by Breton (2006) *'people live in different sensorial universes'*, meaning, each user has a particular perception and interpretation. This issue is of relevance, as still to date **we are missing known, shared guidelines that allow us to group user-related interpretations, facilitating patterns for material selection.**

A recent response to the matter has been **material experience.**
Material experience is defined in the homonym book as *'the experience that people have with and through the materials of a product'* (Karana et al. 2013).
This exploration analyses how the user perceives the proposed outcome according to the **experiential qualities** i.e. what people sense, feel, think, and do in their experiences with and through materials (Giaccardi et al. 2015).

Based on the levels considered for product experience (sensorial, emotional, meaning), material experience adds a new aspect, the performative level. As such, the properties must consider the complex of physical, biological, psychological, social, and cultural conditions that constitute any experience (Giaccardi et al. 2015).

The model proposes that by defining the different levels (sensorial, emotional, performative, and meaning) and comprehending how they parallelly affect each other they could define the different experiences people obtain during the interaction, and eventually help us quantify the unclear subjectivity involved in this spectrum of the materials science.

Translation of each level can be observed in Figure 8.

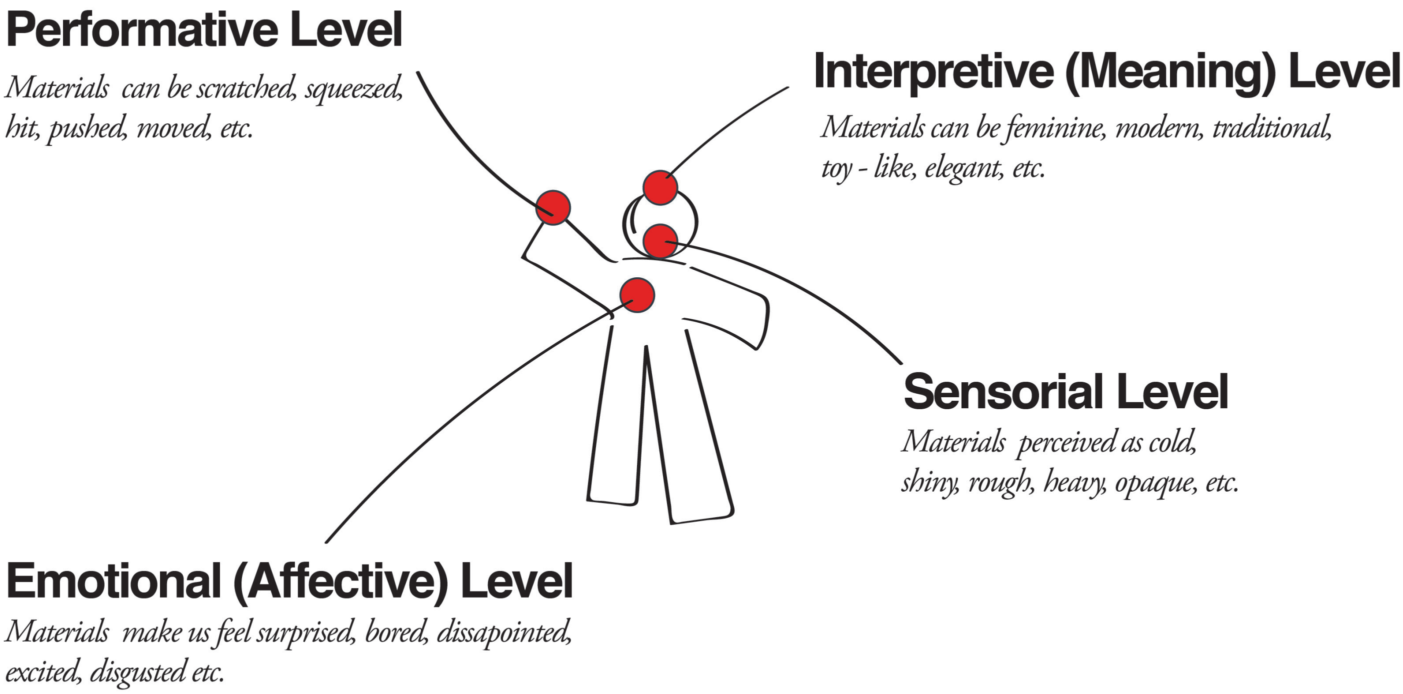


Figure 8. Four experiential levels of how materials are experienced. Source: Garcia and Rognoli, 2019

Then, material experience considers factors of extrinsic information and intangible properties, **helping to comprehend how to evaluate information that otherwise could seem abstract.**

Tools such as the **Ma2E4 toolkit,** developed by Camera & Karana (2018), an acronym for *'Materials-to-Experiences at four levels'*, target to speed up user studies under experiential qualities.
By detecting **pain points during the stages of research and selection processes in design**, e.g., **limited time and skills to invest in user studies**, they stated a preference for qualitative and self-developed toolkits over structured and quantitative studies (Koskinen et al. 2013; Sanders et al. 2010).
The toolkit proposes to define materials through samples connected to images and adjectives specially designed for each of the four levels.
Visual and simplified-text-based representations of objects, aim to bridge the dualist perspective needed to understand materials (technical properties and experiential qualities).

Created to support active research for the experiential qualities characterization, each level was optimized and adjusted through iterations that involved user participation e.g. workshops.

It presents two sets of words (the affective and the interpretive vocabulary), displayed in Tables 1 and 2, plus a collection of images to help define at the interpretive level.

INTERPRETIVE LEVEL

	OR	
Aggressive		*Calm*
Cozy		*Aloof*
Elegant		*Vulgar*
Frivolous		*Sober*
Futuristic		*Nostalgic*
Masculine		*Feminine*
Ordinary		*Strange*
Sexy		*Not sexy*
Toy-like		*Professional*
Natural		*Innatural*
Hand-crafted		*Manufactured*

Table 1. Interpretive level (set of meaning). Source: Camera and Karana, 2018

The elaboration of both vocabularies aims to work as an auxiliary for the material description, to facilitate and support the communication of experiences. Then, by grouping keywords of each with a particular kind of user/context related to a material, it would be possible to elaborate on general aspects (i.e. a pattern) for a defined outcome.

AFFECTIVE LEVEL

OR	
Frustration	*Love*
Boredom	*Amusement*
Disappointment	*Surprise*
Reluctance	*Confidence*
Confusion	*Enchantment*
Rejection	*Respect*
Disgust	*Attraction*
Melanchony	*Curiosity*
Distrust	*Fascination*
Doubt	*Comfort*

Table 2. Affective level (emotional). Source: Camera and Karana, 2018

For the sensorial level, a set of 12 properties on a scale from -2 to 2 evaluates if the material is opaque or transparent, though or ductile, smooth or rough, etc. While the performative level focuses on how the material is touched (e.g. pressing, caressing, or rubbing), moved (e.g. folding, lifting, or picking), and hold (e.g. sizing, pinching, or grabbing).

The Ma2E4 toolkit is briefly introduced to exemplify how intangible aspects can be evaluated, permitting a more organic analysis of the aspects that comprehend the interaction.

After the analysis delivered in this chapter, it is possible to summarize that interaction between people and objects gives rise to material experiences, but **interaction is a flux activity**. Materials, people, and practices come into relation with each other both ‘at the moment’ i.e. when encounters occur, and ‘overtime’, i.e. when performances and collaborations unfold into ongoing practices, engaging dialogue based on sensory language through product’s shape, temperature, color, light intensity, smell, sound, etc. This dialogue is able of variations, dependent on the circumstances and the nature of the material (Giaccardi et al. 2015; Colombo & Rampino, 2013).

The previous statement acknowledges the fact that materials interpretation can change over time. Some materials’ characteristics provide a faster frequency for interpretation change than others, justified by the dynamism of response they can produce. Cases of dynamic change are the focus of the next chapter, taking luminescent material (i.e. light-responsive to energy stimulus) as the study case for this thesis.

Chapter summary

Materials are the interface between products and people.

With each era, new methodologies, technologies, and perspectives are translated into the way we design products. The digital one is no stranger to this condition, boosting awareness from the information the material, the user, and his/her context-background can deliver to the outcome of product and service creations, experiences.
Current proposals pose that experiences can be broken down in terms of technical, sensorial & intangible properties. This notion enables us to conclude that an experience can be formulated if the parameters are well recognized and established.

Through this chapter, we have reviewed the variables that lay the ground for material analysis under interaction means.
In the next chapter, we will in-depth the topic by studying the characteristics of materials with a dynamic change. This thesis centers the attention on a particular kind due to its impact and revolution in the product design field: **Luminescent materials.**
Their characteristics will be analyzed, studying variables that could facilitate their understanding, accelerating its incorporation through a core stage of the field, the material selection process.

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Chapter 2:

Material categories and classifications:

luminescent materials

'To be meaningful to design or engineering, the information on materials has to be expressed (and quantified whenever possible) in terms of functionality [usability and/or satisfaction] instead of just elementary physical properties.'

Lefebvre et al. 2014

2. *Material categories and classifications*

Materials used to be considered a physical invariable entity. Such a notion started to get deconstructed during the sixties through technological advances like the incorporation of computational calculus applied to material science. Studies such as mathematical simulations and microstructure analysis reformulated our understanding of them and expanded their limits.

In-depth knowledge of matter and its behavior at the nanoscale has led to the acknowledgment that **matter can be variable and varied, between tangible and intangible nature** (Ferrara & Bengisu, 2014).
Nowadays there is recognition of materials capable of shifting their physical form into a temporal one, either by providing a shape-change or by generating the illusion of it (Barati et al. 2015; Rasmussen et al. 2012). **This change occurs in certain materials once exposed to an energetic stimulus and has a direct impact on the user experience.**

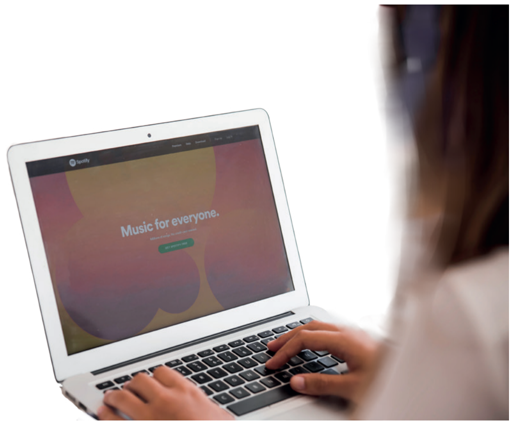
With the notion of dynamism, Parisi et al. (2018) were able to identify three primary categories of materials according to their nature, degree of 'smartness', and their level of interaction, with humans and non-humans (then referred to as, connectivity).
Named Inactive, Reactive, and Proactive materials, they are defined as follows[1]:

> **Inactive Materials:** Unaltered - passive to interaction. Comprehends **traditional and high-performance[2] materials** that don't respond during the interaction encounter, e.g. traditional materials such as wood, ceramic, metal, etc.
>
> **Reactive Materials:** Transmute - response to external stimulus. This kind characterizes by answering energetic stimulus with transmutation either of properties or energy. The changes are perceptible by human organs. Comprehends **smart materials and enhanced inactive materials** integrated with smart components like color-changing pigments.
>
> **Proactive Materials:** Transform - variation of intrinsic responses. **Systems composed of Inactive or Reactive materials joined to micro-devices**, i.e. sensors, activators, or others connected to a computer medium, also defined as Computer composites (Vallgrda & Redström, 2007).

The last two categories, Reactive and Proactive enter the classification of **ICS Materials**, Interactive, Connected, Smart (Parisi et al. 2018).
ICS materials are recognized for being able to **enhance the emotions elicited during and after the interaction or connection, through the product's sensory language, creating new levels of complexities in the experiences** (Rognoli & Garcia, 2018; Krippendorff & Butter, 1984).

In the current era, there is an awareness that products convey meaning through their intrinsic and extrinsic information. Previous ones promoted the use of inactive materials by mediums of mass production, conveying a more or less unchanged sensory language since the creation of the product. Now, with the use of ICS materials, the communication of simple and intuitive messages can be exploited by their dynamic sensory features with the user in a physical way, without the need for verbal, iconic, or numeric language (Colombo & Rampino, 2013).

Material Categories



Inactive Materials

Djembe Wooden Table.

Invariable physical form doesn't respond to energetic stimulus.

Designed by Tekura.

Reactive Materials

Photoluminescent paint.

Transmute in physical form, glow in the dark as a response to energetic stimulus (i.e., temporal form).

Unknown brand.

Proactive Materials

Screen: composite of electroluminescent materials and micro-devices.

Transform in physical form, several colors controlled and provided according to the supplied energetic stimulus (i.e., temporal form).

Designed by Apple Inc.

All images were obtained from CC webpages under public domain or attribution-share alike licenses:
Djembe wooden table, retrieved and edited from commons.wikimedia.org
Other examples have been designed and edited using resources from Freepik.com

Figure 9. Material categories examples

Each material can provide one or more states of its physical form, able to remain stable, transmute, or transform in time. Traditional materials e.g., wood, tend to remain in an unaltered physical form while our interaction occurs, while, glow-in-the-dark paint and computer screens present variations of brightness. These materials correspond to the Reactive and Proactive categories. Other examples include changes in shape (i.e. shape-changing material systems), color (i.e. chromic), light (i.e. luminescent), and many more.

Reactive and Proactive materials differentiation falls in the complexity of interaction they can produce with humans (users) and non-humans due to their dynamism.

Research regarding ICS materials has been carried under several headings, Actuated Interfaces (Poupyrev et al. 2007), Expressive forms (Vallgårda and Redström, 2007), and Shape-changing Interfaces (Coelho and Zigelbaum, 2010; Rasmussen et al. 2012) to name a few.
Agree all in that they are dynamic devices able to change their physical properties depending on the interfaces, the user, or the environment (Poupyrev et al. 2007).

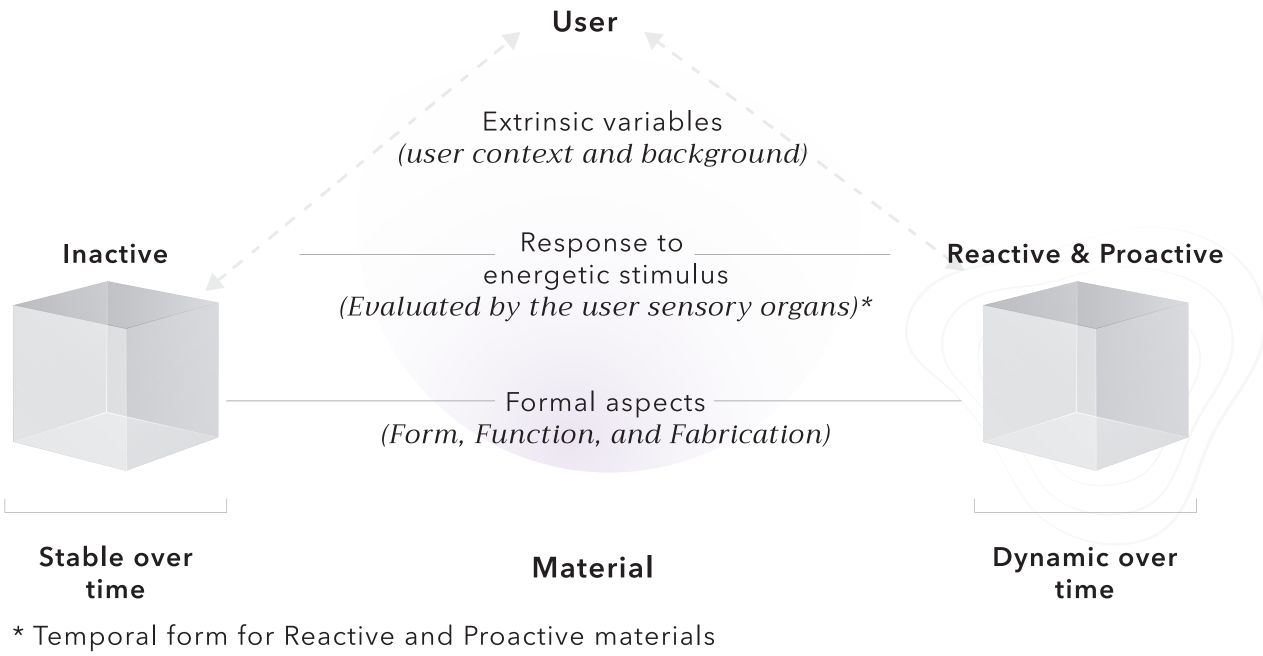
To make sense of these kinds of materials there must be a comprehension of their formal aspects (i.e. form, function, and fabrication) as well as the experience in use (i.e. experiential qualities obtained when the material is in **both non-stimulated and temporal form**) (Barati et al. 2015).

Adding to the information reviewed in Chapter 1, it is possible to conclude there are at least three main aspects to consider that define a material interaction for all categories:

-Material formal aspects - Physical form (Form, Function, and Fabrication)

-Response to an energetic stimulus - Temporal form for Reactive and Proactive (Evaluated by the user sensory organs)

-Extrinsic variables (User context and background)



Based on:
Lefebvre, Esther & Faucheu, Jenny & Pedeferri, M.P. & Delafosse, David & DelCurto, Barbara. (2015). Functional materials for Design.
Ashby, M. F., & Johnson, K. (2013). Materials and design: the art and science of material selection in product design. Butterworth-Heinemann.

Figure 10. Material interaction and its variables

If the interaction is the key point to distinguish the material category, then considerations to both user and material must be provided and covered when approaching the selection of materials.

The previous replies to the ideations presented in section 1.3.2, considering functional-hedonic parameters as well.
As the sections go by, our target will be to translate these variables into technical, sensorial, and intangible properties, for a particular material type.

Being acquainted with the categories is the first step. The following is to understand systems to approach them.

2.1 Materials classifications

A wicked problem regarding ICS is related to their complexity to be incorporated into existing classifications and selection models due to their dynamism, as most of them have been developed for inactive materials. Through this section, we will study classifications to understand how to incorporate them and promote their acceptance.

All material classifications are supported on a base driver. The driver tends to be defined according to the working space, discipline, or point of view, for which the materials will be utilized. Here we can find a breakdown of three classifications elaborated with the information retrieved from Addington et al. (2005); Ashby et al. (2010); Zuo, (2010); Rognoli et al. (2018).

As presented in the historical path displayed in Figure 5, awareness and recognition of materials as a source of emotional meaning is recent, for this reason, the classifications are divided between **traditional and modern kinds**, according to their material coverage and incorporated properties.

Traditional material classifications:

Material Science classification:

Point of view: Dogmatic - Comprehension of material basic structure
Driver: Compositional - bonding forces, internal structures
Considered material categories: Inactive, expanding to Reactive
Type of methodology: hierarchical, science-led (from microstructure to macro-application)
Classification applied in: www.materialsproject.org

Focused on the understanding of bonding forces. It centers the attention on aggregation patterns between atoms, molecular - crystalline structures, to justify the intrinsic properties of each material. At the highest level, broad categories such as ceramics, metals, polymers, and composites can be found.

Engineer classifications:

Point of view: Problem-solving/Pragmatic
Driver: Physical behavior array, application
Considered material categories: Inactive, slowly expanding to Reactive
Type of methodology: mapping, comparative, design-led (macro-requirement to microstructure)
Classification applied in: www.matmatch.com

Centered in narrowing options through defining parameters in the objective spectrum of information (material-technical properties, manufacturing processes, economic requirements) in search to reply to an established scenario.
The broadest consideration of engineer material families presents ceramics, metals, polymers, elastomers, glasses, and hybrids, but this type of classification tends to narrow to a couple of families **according to the industry in which the material will be applied**.

Modern material classifications:

Design Niches - Architectural classification:

Point of view: Product surface, appearance or application
Driver: Artifact visual information
Considered material categories: Inactive, Reactive
Type of methodology: Interpretive, design-led (macro-requirement to microstructure)
Classification applied in: www.materialdistrict.com

This approach seeks to highlight surface qualities of materials, describing characteristics such as composition, form, coatings. Generally, a material profile consisting of selected technical and sensorial properties, supported by visual or qualitative data.

An illustration of the categories under **the response of the material to an energetic stimulus** and together with the coverage of each classification is shown in Figure 11.

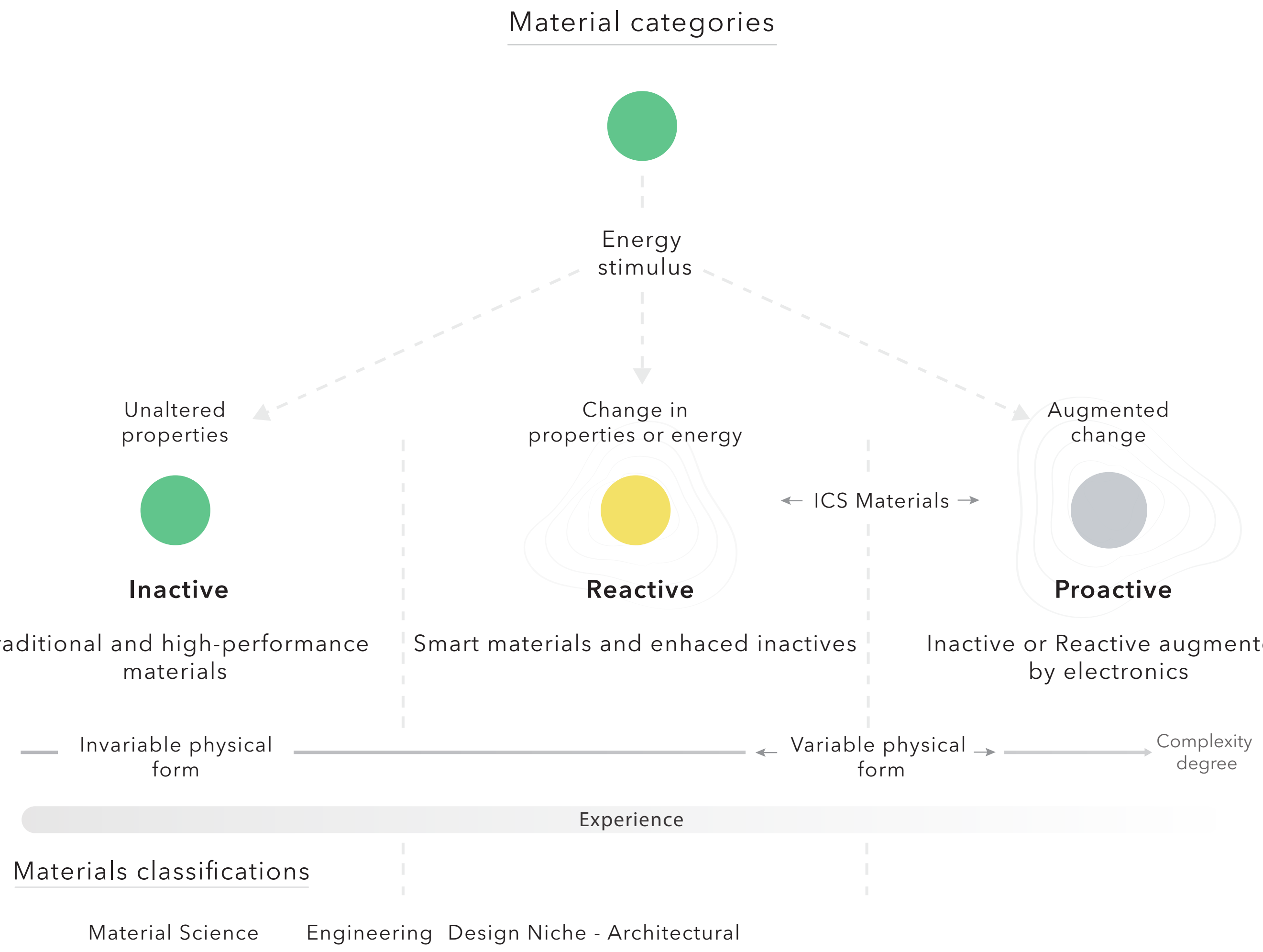


Figure 11. Visual interpretation of current material categories and classifications

Logically, the modern classification has a closer approach to what we have discussed in the previous sections. Even so, we observe that **variables of intangible properties, a key point of material interaction, are not stated as the other ones. Missing also parameters that recognize attributes of ICS materials in the temporal form. Here lays an opportunity for optimization.**

For further analysis of platforms listed as classification examples, please review Chapter 5.

2.2 Reactive materials: Smart Materials

Most people are acquainted with traditional material families such as ceramics, glasses, metals, polymers & hybrids understood as passive to interaction, Inactive materials.

It is the categories of Reactive and Proactive that remain uncertain to most users, and even developers. The complexity falls into recognizing and differentiate such materials and the characteristics that make each of them unique.
Following a design-led approach the sections to come to aim to provide an understanding of the Reactive category and its subcategory Smart materials, until arriving at the definition, working principle, and the making of luminescent materials.

As said, *'when we choose a material, we inherently choose it for its interaction with some type of energy stimulus.'* (Addington et al. 2005) **For the Reactive type, we choose them because of what our organs perceive as a response to an energy stimulus.**

Smart materials are defined by the Encyclopedia of Chemical Technology as *'objects that sense environmental events, will process that sensory information, and then act on the environment'* (Kroschwitz, 1992).
They differentiate from traditional materials and are considered 'smart' due to their ability to 'feel and react' to sensory information (or input), and provide a perceivable outcome (or output) to our human sensory organs.

In other words, **smart materials once faced with an input of energy stimulus, produce change as output, that can be heard, seen, touched, and/or smelled.** The same goes for Inactive enhanced materials, which are modified (internally or externally in their structure) to respond as smart ones.

Moreover, because of their processing capacity, several researchers had chosen to sort them with a **driver** that is not related to their application or appearance. Instead, they do so by **distinguishing the energy stimulus that activates them and the way they react to that stimulus**. This is the case with Addington et al. (2005), Lefebvre et al. (2014), Papile et al. (2019), and the Input-Output energy schemes they have presented.
Furthermore, Addington et al. (2005) has defined **two primary types of smart materials**:

> **Type 1 or Property changing:** the material absorbs the input energy and changes one or more properties. In the case of technical properties, it can affect functional (chemical, optical, electrical, magnetic, thermal) or mechanical properties.
>
> **Type 2 or Energy exchanging:** the material provides energy-transformation changes, meaning the input energy provided mutates when presented as output.
> Type 2 presents a subcategory of smart materials that can reply to a couple of exchangeable input-output energy stimulus, we will refer to them as Type 2 invertible.

Both types respond to the general characteristics of smart materials presenting **direct** (the response is local to the stimulated area of the material), **reversible** (the material can go back to its initial state), as well as **selective** (the transition in the material is repeatable and predictable) **responses to the stimulus** (Lefebvre et al. 2014; Höelter, 2019).

Smart material's value lays in its capacity to produce dynamism of behavior, stimulating our senses, therefore the way we experience each interaction.

Based on the schemes developed by Lefebvre et al. (2014); Bergamaschi et al. (2016); Papile et al. (2019), a proposal for the visualization of these materials is presented in Figures 12 and 13. The organization searches to answer **'how do we want the material to interact?'** and displays a possible structure according to the user's organ the material sensory language would stimulate when in its temporal form.

The distribution of the schemes follows the **type of smart materials we would like to address** (i.e. type 1 or 2)**, the organs desired to stimulate**, linked to the response provided by the material (output), and the specific category that response corresponds to. Finally, the energy stimulus or input should be provided for this outcome to happen.

The first type characterizes by internal molecular or microstructure alteration to the input energy stimulus. This results in a perceptible change in the way it looks, smells, or the thermal sensation it produces.

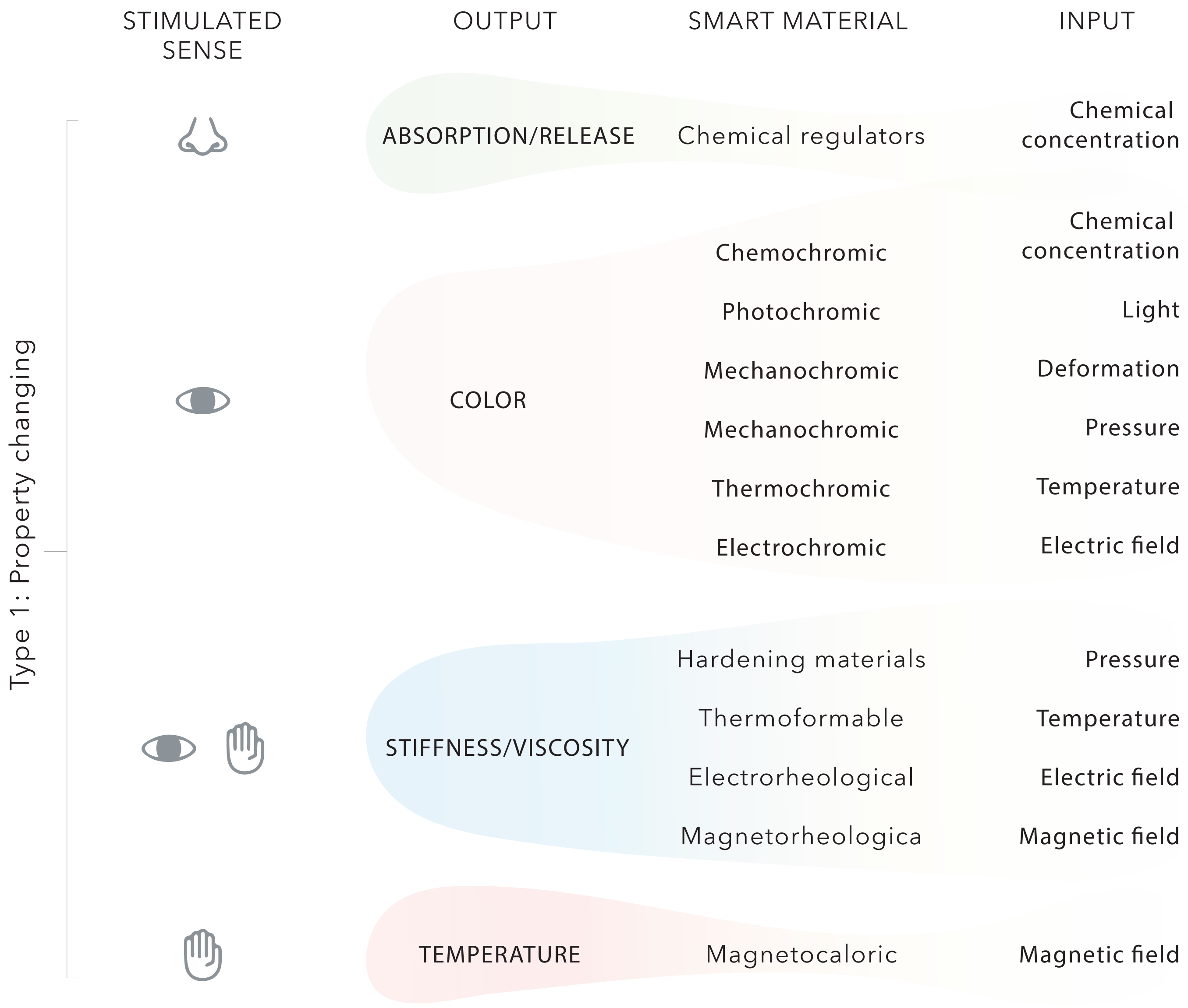


Figure 12. Property changing smart materials, scheme for path recognition

Type 2 functioning involves atomic energy levels.
The input energy raises the level (excites), the output energy returns the level to its ground state (see Figure 16). Figure 13 also shows the energy exchanging smart materials to which input-output energy stimulus can be interchanged, so the process can happen in both directions.

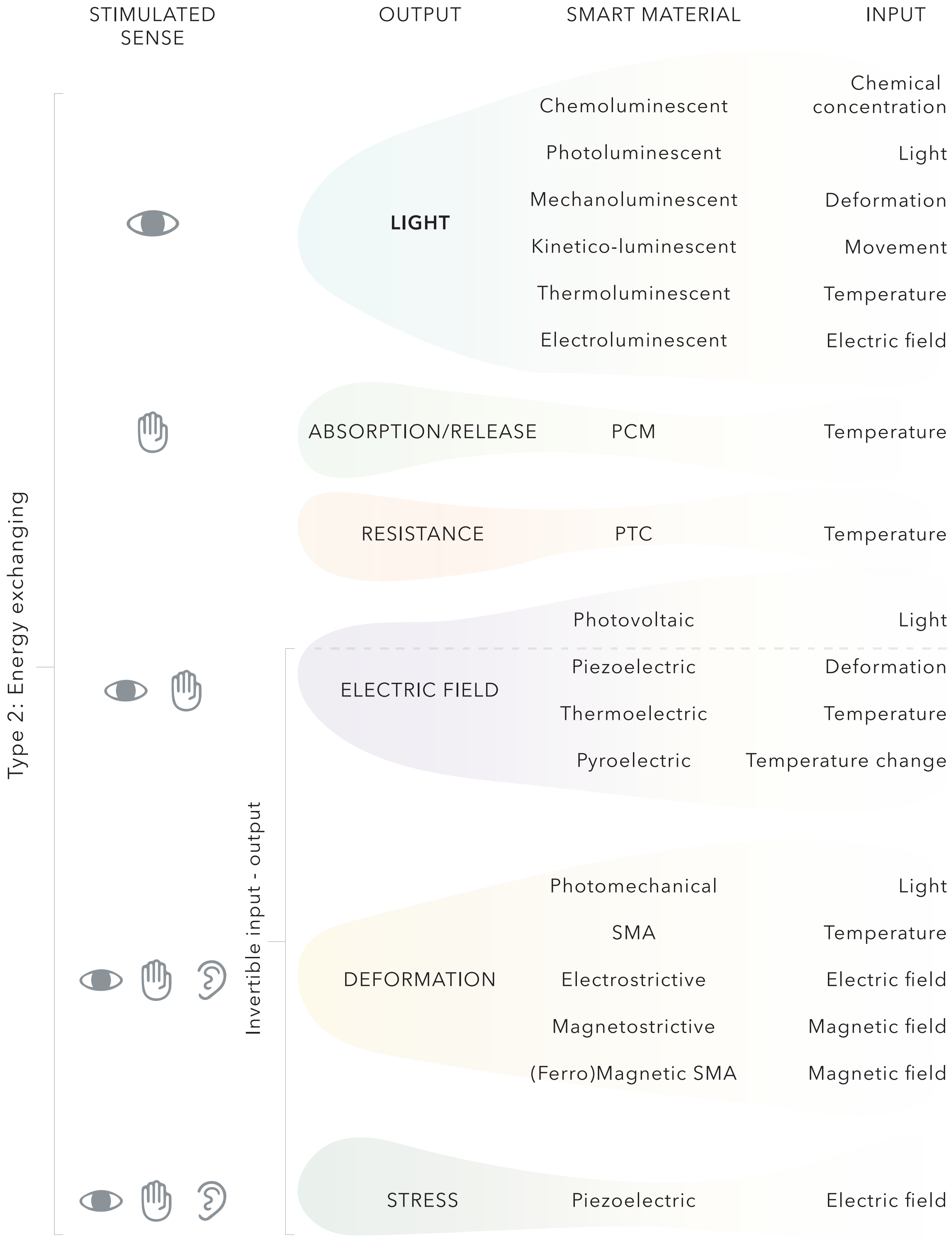


Figure 13. Energy exchanging smart materials, scheme for path recognition

Each of the smart materials listed in the figures understands levels of complexity that need to be explained and evaluated individually. For this particular study, due to their high impact and exponential use in several products and industries, the attention is centered on the **first category of Type 2, Energy exchanging - Luminescent materials.**

By exploring luminescent materials, we will analyze the properties that differentiate them such as the visual sensorial communication provided when stimulated, through their light-emissions in the temporal form.

This type of development and exploration is a sample of the broader technological shift towards integrating composites able to enhance interaction by sensing and actuating.

In the sections to follow, we will observe their working principle, possible uses, and impacts on the field of products, searching to understand patterns that could guide their selection.

2.3 Luminescence: light and nature

Luminescence is a type of light generated by excited electrons and dependant on a supplied energetic stimulus (Addington & Schodek, 2005).

> *'Light is a form of electromagnetic energy. To create light another form of energy must be supplied. There are two common ways for this to occur, incandescence and luminescence.'*
> *Murthy & Virk, 2014*

Incandescence corresponds to the glow obtained from an energy stimulus of temperature difference (heat), related to high temperatures, known as 'hot' light, a phenomenon, where the material gets consumed as the process takes place.
Luminescence, on the other hand, corresponds to 'cold' light. Here the **sources of energy** differences can be **chemical, electrical, kinetic,** to name a few, **providing emissions in ambient or low temperatures. Those able to generate this type of response are also known as** *phosphors*, which means **'light bearer'** in Greek.

This phenomenon is quite common, visible on everyday products as the face of watches, light switches, security marks, light sticks, and glow-in-the-dark ornaments, generated by different stimuli types.
In nature, the process is present in some crystals and phenomenons such as the aurora borealis, most commonly found in bioluminescent marine and terrestrial organisms.

Certain non-vertebrates such as algae and fungus (e.g. noctiluca scintillans, panellus stipiticus), insects (e.g. glow worms, glowing cockroaches), and fishes (e.g. malacosteus), can emit light by bioluminescence. This particular type of luminescence occurs by catalyzation in enzymes of living organisms. Is a reaction where the whole relaxation energy is emitted as light with neglective heat dissipation, being considered as 100% efficient, providing the origin of the term 'cold light' (Szakmány, 2013).

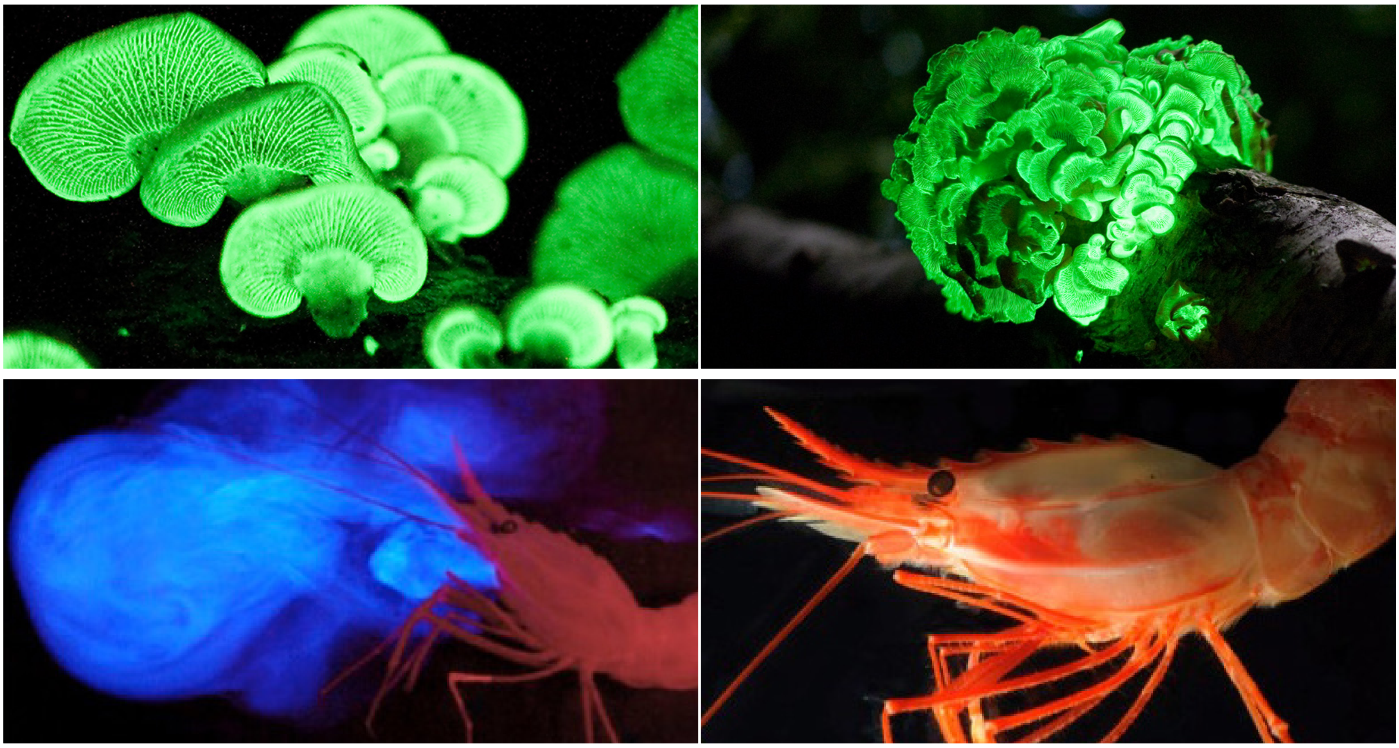


Figure 14. At the top: Panellus stipticus displaying bioluminescence. At the bottom: pandalid shrimp. Source: commons.wikimedia.org. Category: Bioluminescence

Both the color and purpose of bioluminescence depend upon the organism's habitat.

Organisms emit light to communicate, to attract food, for mating purposes, and as a defense against predators (e.g. camouflage). An example of this can be seen with some shrimps species who can vomit out brightly luminescent blue-green slime at enemies when they are threatened as presented in the bottom images of Figure 14.
Moreover, the ambient plays a key role in bioluminescence. Most of the deep-sea species emit blue light, coastal marine species are recognized by their green emission, while there are terrestrial and freshwater red shifters (Kahlke & Umbers, 2016). The corresponding color of bioluminescence in different habitats can be observed in Figure 15.

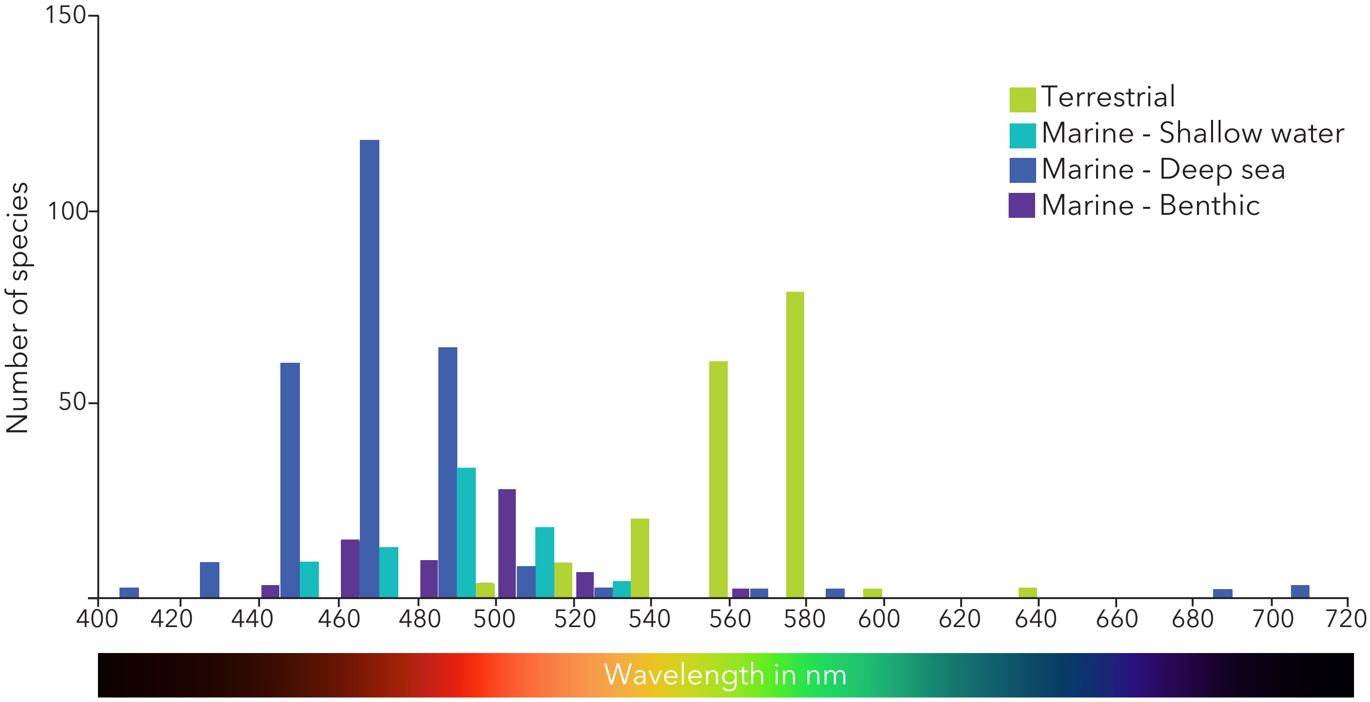


Figure 15. Light spectrum in nature. Source: Kahlke & Umbers, 2016[1]

Bioluminescence has inspired several creations through biomimicry (i.e., method of studying nature to create or develop sustainable solutions for human problems) mainly by its diversity of results (e.g. brightness, colors, and time emissions) in addition to the potentiality to 'regenerate' providing continuous illumination.

Moreover, with the growing concerns regarding climate change, and the negative impacts produced by conventional energy sources, is that a search to produce environmentally benevolent technology has been set since the middle of the nineties, aiming to provide compact, cost-effective, energy efficient, UV free and environmentally friendly with wide variety of designable features (Nakamura, 2017)
Today's smart lighthing solutions search to mimic the reversible and selective responses of nature luminescence, providing predictable temporal lights especially appreciated in dark environments, when or after being stimulated (Liang et al. 2013).

Luminescent materials correspond to substances, insulators, or semiconductors, generally doped with minerals or small impurities, in charge of converting incident energy, into emitted electromagnetic waves in the ultraviolet (UV), visible, or infrared (IR) regions of the electromagnetic spectrum.

1 Redrawn from Bioluminescence in the ocean: origins of biological, chemical, and ecological diversity. Science,Widder, E. A. (2010). 328(5979), 704-708. Copyright (2020), with permission from Elsevier and AAAS.

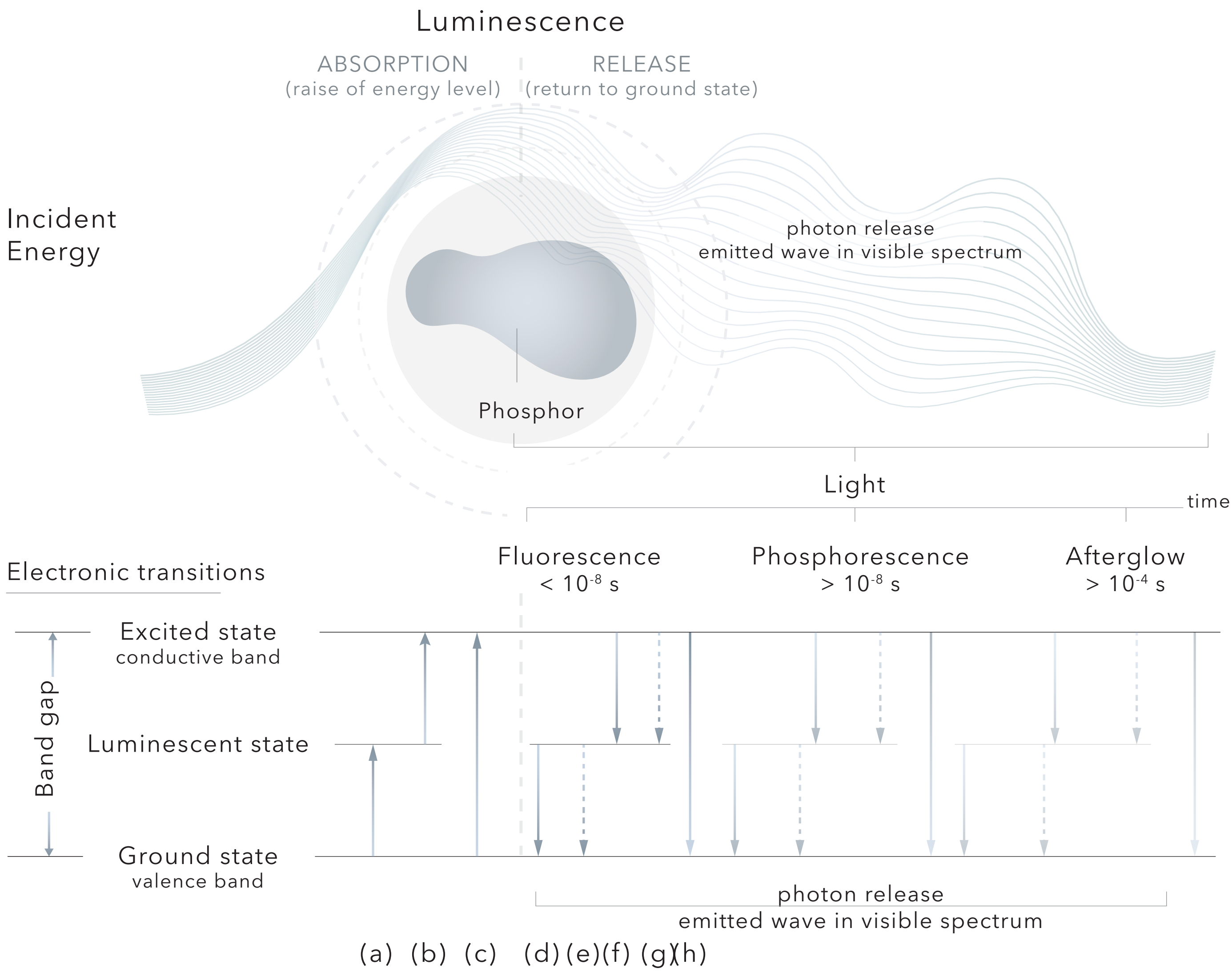
Their general composition consists of a host lattice plus an activator, such as transition metals, (e.g. zinc sulfates with tiny amounts of copper, or rare-earth elements), produced as bulk powders, nanoparticles, or metal-alloys (Kasap & Capper, 2017; Liu, 2016).

The functional approach of these materials usually fixed on the visible spectrum, covers a specific **range of energy** (1,65 eV to 3,50 eV), **frequency** (from 4*1014 to 8*1014 Hz), and **wavelengths** (between 750 nm to 380 nm) (Monette et al. 2019).
This spectrum enables us to visually distinguish the objects surrounding us, their colors, textures, reflection, having an important relevance in the material interaction.

Various types of luminescence can be produced, which depend upon the interaction between the electronic system of the luminescent centers and the vibrations of the atoms or ions surrounding the environment. The luminescent material properties such as the spectral position of the absorption and emission bands as well as the decay time of the emission play a key role and will determine their suitability for different application fields such as medical, defense, and construction (Sawdea et al. 2019; Iyer, 2020).

The working-principle for these kinds of materials is through **differences in the atomic energy levels,** listed as follows and displayed in Figure 16:

(a) Incident energy will enter, the absorption process will start.
(b & c) Electrons will get excited and 'jump' to a higher state.
(d, e, f, & g) After some time, the release or decay of electrons will occur in the form of radiative and non-radiative transitions.



Electronic transitions section based on Jablonski-diagrams presented in:
Werts, M. H. V. (2005). Making sense of lanthanide luminescence. Science Progress, 88(Pt 2), 101–131.
Kasap, S., & Capper, P. (Eds.). (2017). Springer handbook of electronic and photonic materials. Springer.

Figure 16. General aspects of luminescence and electronic transition in their materials. (a) absorption/excitation from valence band or ground state, (b) excited state absorption, (c) direct excitation into a higher state from valence band or ground state, (d) 'conventional' emission from the lowest luminescent state, (e & g) non-radiative relaxations, (f) radiative transitions between excited states from excited state or conductive band, (h) emission from a higher excited state from excited state or conductive band

All luminescence is the result of the competition of radiative and non-radiative pathways in the relaxation/decay of electronically excited species.
For luminescence to occur and materials to be efficient on it, radiative transitions must dominate over the non-radiative ones. **Radiative transitions will provide light (d,f & h)**, while non-radiative (e & g) provides lattice vibrations that transport energy in the form of heat (Murthy & Virk, 2014; Werts, 2005).

From the previous statements, it is possible to conclude that to control or articulate the resulting emission according to desired outcomes it is relevant to recognize the aspects that generate and affect it such as:

The incident energy input, which determines the type of luminescence (see Table 3).

The material composition, phosphor-activator to whom the incident energy will affect. Responsible for the characteristics of the emitted light (further described in section 2.3.2).

The ambient conditions, generally demonstrated as temperature dependant, altering the resulted brightness and speed of the wave.

The resulted wave is a time-domain variable consequence of the three previous.

The potentialities of luminescent materials consider the activation time (i.e., the time needed for the effect to occur from the moment the input is received), and the **relaxation time** (i.e., the time needed for the material to turn back to its initial state) presented during their temporal form (Papile et al. 2019).
Both concepts are implied in Figure 16 and are described under the definitions provided by Addington & Schodek (2005) and Murthy & Virk (2014) as:

Fluorescence (instantaneous emission = $t < 10^{-8}$ s, decay can be independent of temperature)

Phosphorescence (delayed emission = $t > 10^{-8}$ s, its decay depends on temperature)

Afterglow (long-delayed emission, light emission long after the source of excitation is removed = $t > 10^{-4}$ s, its decay depends on temperature).

Characteristics that are common in luminescent materials include:

- **Selectivity**: the transition(s) occurring in the material is predictable and repeatable

- **Reversible change**: once a change has occurred, the material can turn back to its initial state. Variating in the possibility of that change to be,

  - **Single change**: one change occurs at a precise value of the input, giving the material two states between which it switches.

  - **Continuous change**: the change is gradual occurs between two values of the input.

  - **Multiple change:** several changes can occur at precise values of the input.

If the material cannot go back to its original state, the it is considered to be irreversible[2].

Another aspect we will observe further ahead is that most of these materials do not need continuous stimulation to produce light.
Some of them can store it and release it gradually while others are in constant need of excitation to work, this characteristic will be included in the analysis displayed in section 2.3.3, Table 5, under the indicator of 'Constant supply of excitation source'.

In the sections to come the material types and their activation stimuli will be discussed. Cases retrieved from the literature review and database will provide insights for their exploration.

2 Some cases such as chemiluminescent reactions are not reversible e.g., glowsticks.

2.3.1 Types of Luminescence

The type of luminescence depends on the source of excitation or input of energy supplied.

The input stimulus is one of the most important aspects to consider when working with luminescent materials as it is the origin for the emission. It is highly relevant when considering the industry of application, color emission, and modularity, as it can guide the selection type of material to accommodate the needs.

From literature review (Addington & Schodek; 2005; Lefebvre et al. 2014; Bergamaschi et al., 2016; Papile et al. 2019) it is possible to distinguish at least nine different types of luminescent phenomenons, declared up next with their corresponding input or excitation source in Table 3:

Luminescent phenomenon	Abbreviation	Mode of excitation
Chemiluminescence	CL	Chemical reaction
Bioluminescence	-	Biochemical reaction
Photoluminescence	PL	Absorption of light
Mechanoluminescence or triboluminescence	ML	Frictional and electrostatic forces
Themoluminescence	TL	Ionazing radiation
Electroluminescence	EL	Electric field
Cathodoluminescence	-	Cathode rays
Sonoluminescence	-	Ultrasound
Kinetico-luminescence	-	Movement

Table 3. Various types of luminescent phenomenons

Supported by remarks extracted from Hughes (2008), Kasap et al. (2017), Murthy et al. (2014), Xie et al. (2018), and Wu et al. (2020), five types of luminescence are further reviewed according to their impact in product development for several industries.
Chemiluminescence, Photoluminescence, Mechanoluminescence, Thermoluminescence, and Electroluminescence are listed accompanied by their working principle, relevant indicators, and associable examples to introduce potentialities of these materials in their **temporal form** (i.e. when emitting light).

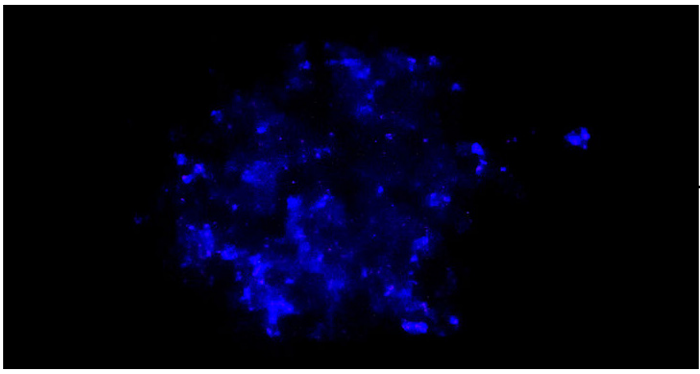
Figure 17 displays basic examples of each of the selected types of luminescence.

Chemiluminescence
glowsticks

'The Kids And The Glow-In-The-Dark Glasses On Our Hotel Balcony' by Joe Shlabotnik at creativecommons.org

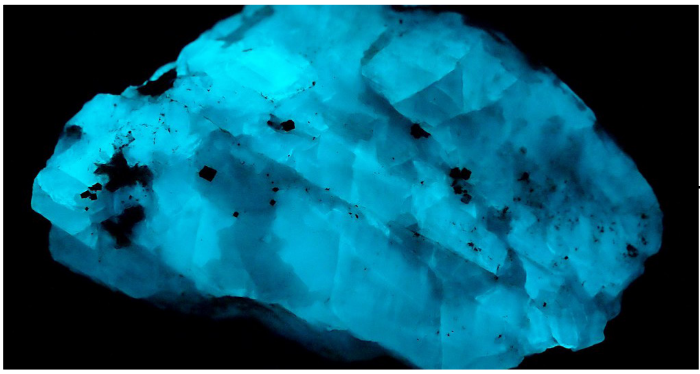
Photoluminescence
face of watch

'Glowing in the dark' by Stratman at creativecommons.org



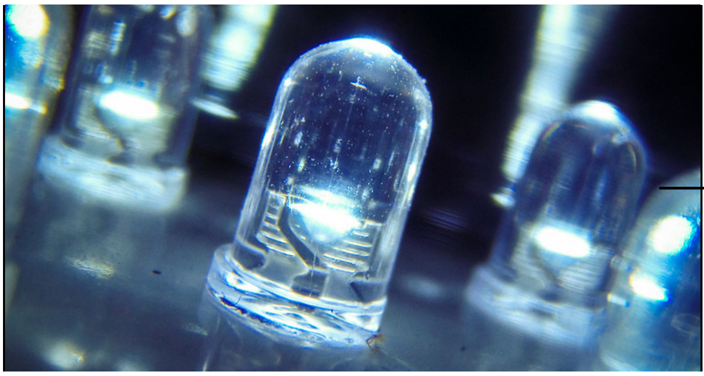
Triboluminescence
nicotine silicate

'Nicotine-L salicylate' by H.Hiller at commons.wikimedia.org, category: Triboluminescence



Thermoluminescence
chlorphane

'Connecticut Fluorite (var. Chlorophane) - PHOS' by someHerrings at creativecommons.org



Electroluminescence
White Led

'#31 LED' by Mike Deal at creativecommons.org

Figure 17. Familiar examples of selected luminescent types

The indicator luminous efficiency, which corresponds to the *'measure of brightness obtained by dividing the source's luminous flux by the consumption of its energy'*, according to the International System of Units (SI) is introduced in this section due to its remark in the literature review.

Luminescent materials shine is generated by radiative relaxation emissions, excelling over their competitor, incandescence, where most of the output gets released in the way of heat, i.e. non-radiative emissions, for this reason, the incandescent lamp is known for providing mainly warmth while generating a luminous efficiency in the order of 5%.

Characteristics of each type include:

Chemiluminescence (CL)

Energy input: Chemical reaction
Temperature dependant: Yes
Emission duration: Fluorescence to afterglow
Luminous efficiency: up to 23%
Luminous colors: Wide variety in the visible spectrum

Chemiluminescence reactions start with an oxidizing agent carried into an unstable peroxide, making a light-emission-material in its excited state; it then rapidly decays emitting radiative relaxations (i.e. photons) over non-radiative (i.e. phonons), following the steps presented in Figure 15. The most known chemiluminescent reaction is an alkaline solution with hydrogen peroxide in the presence of iron or copper, which provides a bright bluish result, known as Luminol.
Chemiluminescence subset that happens in nature corresponds to **Bioluminescence** as described previously and displayed in Figure 14 and 15.

Photoluminescence (PL)

Energy input: Light - radiation energy from the electromagnetic spectrum (photons)
Temperature dependant: Yes
Emission duration: Fluorescence to afterglow
Luminous efficiency: up to 20%
Luminous color: Wide variety in the visible spectrum

Due to energy conservation, in this process the material releases a longer wavelength of light with a lower energy level than the one received (i.e. down-conversion). PL efficiency gets higher when stimulated with a shorter-higher frequency wavelengths e.g., ultraviolet light. Found in coatings or mixed in with other materials, it is also present at the second stage of fluorescent lights, where an electric current excites mercury vapor, which produces short-wave ultraviolet light (electroluminescence) stimulating a phosphor coating on the inside of the lamp to glow (photoluminescence).

Mechanoluminescence or Triboluminescence (ML)

Energy input: Deformation- ripping, scratching, pulling. Break of chemical bonds.
Temperature dependant: -
Emission duration: Fluorescence, phosphorescence
Luminous efficiency: Up to 59%
Luminous color: Wide variety in the visible spectrum

The emission takes place during the mechanical separation of surfaces or when crystallization occurs (i.e. elastic/plastic deformation, and fracture of solids). During the process, positive and negative electric charges are produced and trapped carriers at defects get released with the help of stress. It is light emission by discharge, either directly, by molecule fragments, or via excitation of the atmosphere in the neighborhood of the separated surface, as seen in sparkles obtained by crushing sugar crystals or quartz (SiO_2) or nicotine silicate (see Figure 17).

Thermoluminescence (TL)

Energy input: Ionizing radiation - irradiation rays
Temperature dependant: Yes
Emission duration: Phosphorescence, afterglow
Luminous efficiency: -
Luminous color: -

It works by the emission of previously absorbed energy when **crystalline materials** are heated.
When the solid is irradiated, electrons and holes are produced, which can be trapped at defect sites. Under the heat stimulus, the trapped electrons/holes get enough thermal energy to jump the band gap from the ground state (i.e. valence band) to the excited state (i.e. conduction band), see Figure 20. From there they may get re-trapped again or may recombine with trapped holes/electrons. If this recombination is radiative, then luminescence happens. In the case of non-radiative, there won't be luminescence. **The amount of luminescence is proportional to the original dose of radiation received,** for this is a common geochronology tool for dating pottery or other fired archeological materials.

Electroluminescence (EL)

Energy source: Electric field - electric current passing through a substance
Temperature dependant: Yes
Emission duration: Fluorescence
Luminous efficiency: Up to 50%
Luminous colors: Combination currently allows all visible spectrum

EL is considered as an efficient generation of light in a non-metallic solid or gas by an applied electric field. This type of luminescence is the most exploited currently. Thanks to designed semiconductor materials where their selected 'dopants' or impurities allow controlled electron movements, then, 'personalized' electrical properties.
Exploided electroluminescent products correspond to Solid State Lighting (SSL) light-emitting diodes (LEDs), organic light-emitting diodes (OLEDs), and polymer light-emitting diodes (PLEDs) which are the outcome of current passing through a semiconductor material made of inorganic, organic or polymeric materials with different forms and the avility to provide multiple changes (i.e., range of color and brightness responses).

A summary of the general characteristics of each type discussed in the section is illustrated in Figure 18.
It is important to notice that these are presented as a general guidance, as the results can change once the materials have been treated for their affordance.

The maturity of each type has been incorporated according to the statements declared in the complementing articles listed in this section.

*Triboluminescent products are still in early maturity, but their entrance to several markets promise to be fast and soon.

Figure 18. Summary of luminescent types characteristics

2.3.2 A brief understanding of rare-earth ions

Luminescent materials are classified into two basic groups: metal oxide semiconductors that have large band gaps, absorb ultraviolet (UV) light, and emit visible light, and metal oxide insulators (i.e. host materials) doped with luminescent transition metal ions (i.e. activators) (Fujihara, 2013).

There are several types of activators, nonetheless, technology is currently dependant on the 17 Rare Earth Elements (REE), as stated by the International Union of Pure and Applied Chemistry (IUPAC). Most of the new technologies introduced in the world rely on the properties of selected functional materials (e.g., luminescent ones). In the majority of the cases, these are or contain metals, metal alloys, or metal compounds. Very often, the quantities of the functional materials are very small but indispensable for the main functionality of tech products (Vogel, 2011; Damhus et al. 2005).

The set of REE is displayed in Grouped in IIIB, from period 4 to 6 of the periodic table, and can be found as accessories in minerals as they don't occur in pure. They are not as difficult to find as their name could mislead, as they are complex/costly to mine and clean.

REE presents outstanding characteristics such as electropositivity, narrow emission bands, sharp emission spectrum for high color purity, and long decay times, considered as high electrical conductors. Such attributes have provided them use in wide fields of occupation, behaving as bricks in today's medical, and military applications, improving lifestyles & communications, reducing weight, uplifting energy efficiency, mitigating consumption and products emissions (Vogel, 2011; Mudring et al. 2006; Voncken, 2015; Xu et al. 2019).

From the total set of 17 elements, 15 correspond to Lanthanides, (atomic numbers 57 to 71 in the periodic table), the other two are scandium and yttrium, transition metals. The fifteen lanthanides tend to present trivalent lanthanide ions, dominant valence state in +3 (Ln+3) one of the sources for their unique photophysical properties.

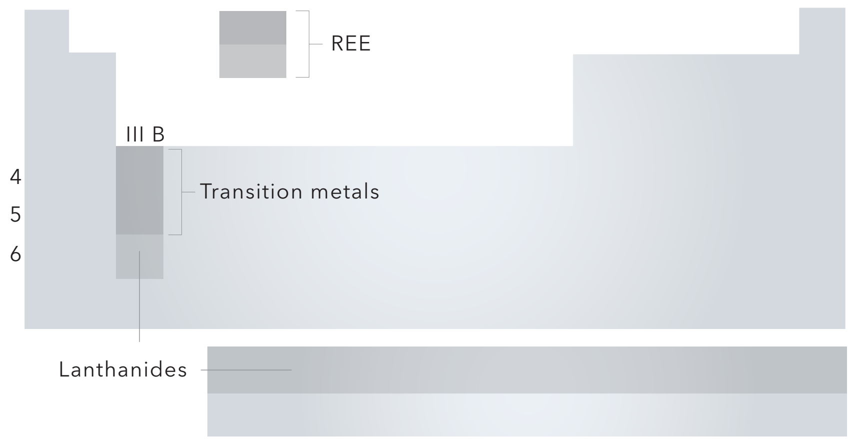
Rare Earth Ions of lanthanides (REI) play a key role in luminescent materials as **if one would succeed to introduce lanthanide ions into a particular material, be it a crystal, a glass, a liquid, a molecular material such as a polymer, this material will become luminescent** (Werts, 2005).

REI activators in luminescent smart materials, characterize for producing emission spectra seemingly independent from their host lattice that enables high lumen efficacies and transmits information very well perceived in the human eye (Ronda et al. 1998).

Their relevance is partly related to the fact that color belongs to light and is through the phosphors that color can be modulated and tuned for desired experiences. The procedure is carried by mixing or varying ratios of activators in composite materials (see Figure 30), it can also be done by masking the color emission through dyes applied in the selected matrix of the material (Monette et al. 2019).

To modulate color it is necessary to know three quantities – **energy, wavelength, and bandwidth.** The previously mentioned correspond to qualities of light and are related to intensity and spectral composition. The **energy level tells us how bright, the wavelength tells us which hue and the bandwidth tell us what saturation of a color** (Addington & Schodek, 2005).

Figure 19 illustrates and contextualizes REE and REI used in luminescent materials. The incorporated table organizes the most commonly used REI and their characteristics.



REE:

Transition metals:

scandium (Sc), yttrium (Y).

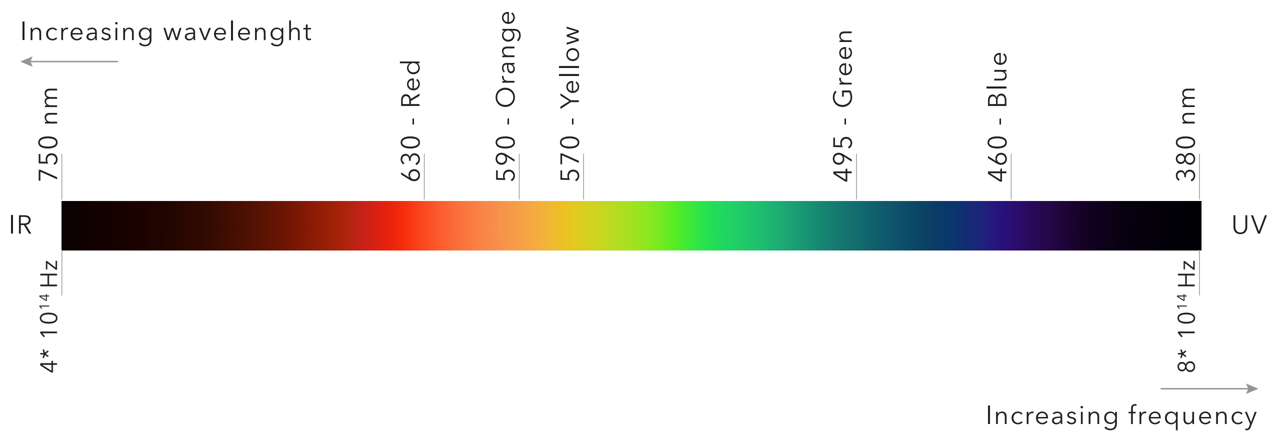
Lanthanides:

cerium (Ce), dysprosium (Dy), erbium (Er), europium (Eu), gadolinium (Gd), holmium (Ho), lanthanum (La), lutetium (Lu), neodymium (Nd), praseodymium (Pr), promethium (Pm), samarium (Sm), terbium (Tb), thulium (Tm), ytterbium (Yb).

Element	Y	Ce	Pr	Eu	Gd	Tb	Sm	Dy	Er	La
Use in lumin.	Major	Major	Major	Major	Major	Major	Minor	Minor	Minor	Minor
Color of visible lumin.			From red to white	Red/ orange		Blue/ Green	Red/ orange	Yellow	Green	
Emission intensity				Strong		Strong	Medium	Medium	Weak	
Atomic number	39	58	59	63	64	65	62	66	68	57
Orbitals	$4d^1 5s^2$	$4f^2 6s^2$	$4f^3 6s^2$	$4f^7 6s^2$	$4f^7 5d^1 6s^2$	$4f^{10} 6s^2$	$4f^6 6s^2$	$4f^{10} 6s^2$	$4f^{12} 6s^2$	$5d^1 6s^2$
Oxidation state	+3	+3/+4	+3	+2/+3	+3	+3/+4	+2/+3	+3/+4	+3	+3

Lanthanides

Visible spectrum



Information retrieved from:
Voncken, J. H. L. (2015). The Rare Earth Elements An Introduction: Physical and Chemical Properties of the Rare Earths
Vogel, N. (2011). Springer Theses
Werts, M. H. V. (2005). Making sense of lanthanide luminescence
Xu et al., (2019). Luminescent colour modulation of a multicolour praseodymium activated phosphor.

Figure 19. REE and REI used in luminescent materials

The lower part of the image incorporates a scale of the visible spectrum, enabling the reader to relate the range of visible color to the wavelength and frequency of each element.

For example, europium (Eu) is known for its red-orange emission with a wavelength over 590 nm, while terbium displays a green-blue luminescence with around 460 and 495 nm. The combination of these two in a variety of ratios can enable different colors of the spectrum, able to achieve a bright white luminescence in a ratio of 4 to 96 for the hydrogel form as shown in Figure 30 (Chen et al. 2015).

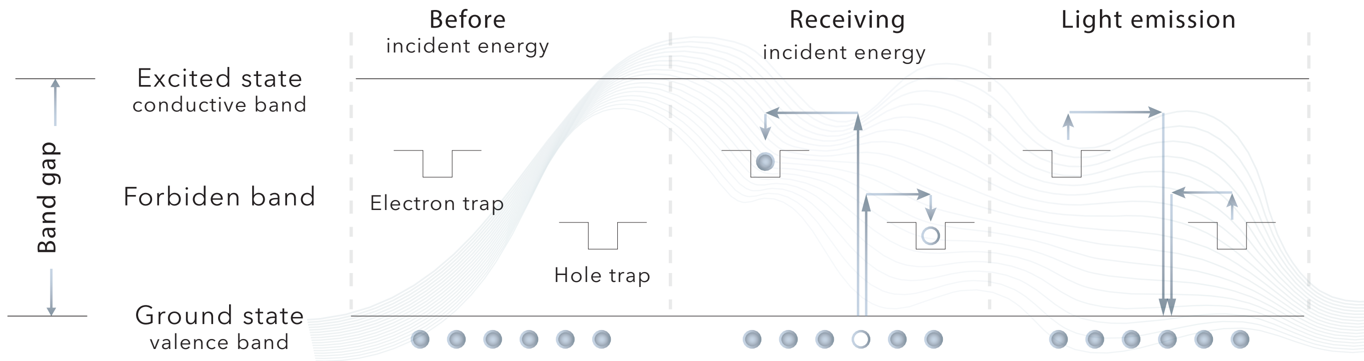
Understanding the impact REI has on the luminescent outcome enables us to see the selection approach for these types of materials. Either starting by a the micro-selection, explaining the implications of using a particular element (REI) in a bottom-up approach, e.g. the emission displayed will be in red, in a liquid form, in a frivolous environment, with inactive interaction, to produce XYZ interpretation. Or arriving at the element by defining the outcome experience, luminescent type, efficiency, color spectrum, and so on in a design-led path.

Independent of the case the reality is that playing with crystalline/powder variations, concentration amounts, and dopant sizes are the key to engine

Quests regarding luminescence range from improving the phosphorescent effect once the excitation source has been removed, i.e., afterglow, to color modulation of REI, providing multicolor answers with one same phosphor (Xu et al. 2019; Ma et al. 2020; Yin, et al. 2020).

An approach to do so is by working with the 'traps' present in the bandgap in between the valence band and conductive band. Based on the electronic band model which assumes the existence of energy excited states in the forbidden band. Incident energy enables mobile carriers, i.e., electrons and holes. The electrons are free to travel from the valence band to the conduction band, meanwhile, the holes remain in the valence band or are free traveling near the ground state. Posteriorly, with light emission, the mobile carriers are released. This model is also used to explain the behavior of thermoluminescence.

Graphical visualization of this concept is presented in Figure 20.



Based on:
Rivera, T. (2012). Thermoluminescence in medical dosimetry. Applied Radiation and Isotopes, 71(SUPPL.), 30-34.

Figure 20. Electronic band model representation

This section has been included to provide notions on the microstructure of luminescent materials. Understanding at the micro-level can lead designers to propose better-developed innovations at the macrostructure.

2.3.3 Making Luminescent materials: luminescent forms

Luminescent materials and products are present in our everyday surroundings. In luminaries, screens, art, and toys. Even so, for most users, and designers, the making of these products remains unknown.
These materials characterize for generally being the result of more than one material family, obtained by incorporating phosphors into a glass, ceramic, polymers, wood, or even natural fibers, in between conductive layers, sandwiched structures, liquid solutions, powder mixtures among others methods.

Through this section, we will review forms in which luminescent materials have been applied and used as products, providing an organizational system to approach them.

As explained, phosphors are composed of a host lattice or matrix and a small amount of activator(s). These are usually synthesized in powder form to generate the desired micro-nano structure according to affordance (Lakshmanan, 2012; Sawdea et al. 2019).
Applications such as LEDs, solar cells, paints, and bio labeling, are the result of luminescence and depend on the synthesis of phosphors into particles with a variety of sizes and morphologies, generally in the nano order.

Nanomaterials characterize for the size of their particles, generally <100 nm; allowing an exceptional surface coverage and exhibiting different properties from their bulk form, particularly in terms of their distinct optical, electrical, thermodynamic, and magnetic properties (Liu, 2016).

The morphology and particle size of the powder play a key role in respect of the intensity, efficiency, and resolution obtained from the luminescent material (Lakshmanan, 2012).
Due to their impact, materials can be categorized according to their dimension in the order of:

- **0D:** e.g. nanoparticles or dots
- **1D:** e.g. nanowires or rods
- **2D:** e.g. thin-films or nano wells
- **3D**: e.g. bulks

This classification is a current approach to understand these materials, but unfortunately, the selected vocabulary could be not straightforward enough to manage in the product design field.

Even now with their impact and use in so many branches, available information of the reactive type is divided between very technical scientific articles or too simplified product presentations in online material databases. In this matter, what can be obtained lacks a connection between possible experience outcomes and fabrication guidelines.
This situation can difficult for design engineers to understand the making of these materials.

A proposal to tackle this problem was presented by Barati et al. (2017) who defined **three basic light forms:**

- **Point** (e.g. LEDs)
- **Line** (e.g. electroluminescent wire, optical fibers)
- **Surface** (e.g. electroluminescent paints)

This breakdown of **luminescent forms** recognizes the physical format of the material (i.e. how the material is presented in its non-activated mode). Nonetheless, the team recognized that for textiles and other flexible substrates the categorization is unable to incorporate them, being difficult to label them due to the variations they can produce in experiential qualities at the performative level (e.g. squizzed, rubbed, touched).

Aiming to explore methods of fabrication, several articles and databases were studied. The collecting of products, publications, and concept studies on the subject of luminescent materials led to over 25 proposals. A total set of 16 luminescent materials, were further analyzed due to their appliance, novelty, development period, and stated manufacturing processes. These were categorized according to the industries in which they are or would be applied.

Uses covered from Transparent Luminescent Solar Concentrators (TLSC), photoluminescent reprintable paper for confidential information (She et al. 2019), mechanoluminescent paint for construction structures to detect crack propagation (Timilsina et al. 2017) to flexible electroluminescent fibers for wearable electronic textiles (Zhang et al. 2015).

The selection present cases in the development status of concept state (n°13), experiment (n° 2 & 9), prototype (n° 4, 5, 7, 8, & 14), and product (n° 1, 3, 6, 10, 11, 12, 15 & 16), this last one highlighted in grey.

Figures 21 and 22 present images of studied cases, further described in Table 4.

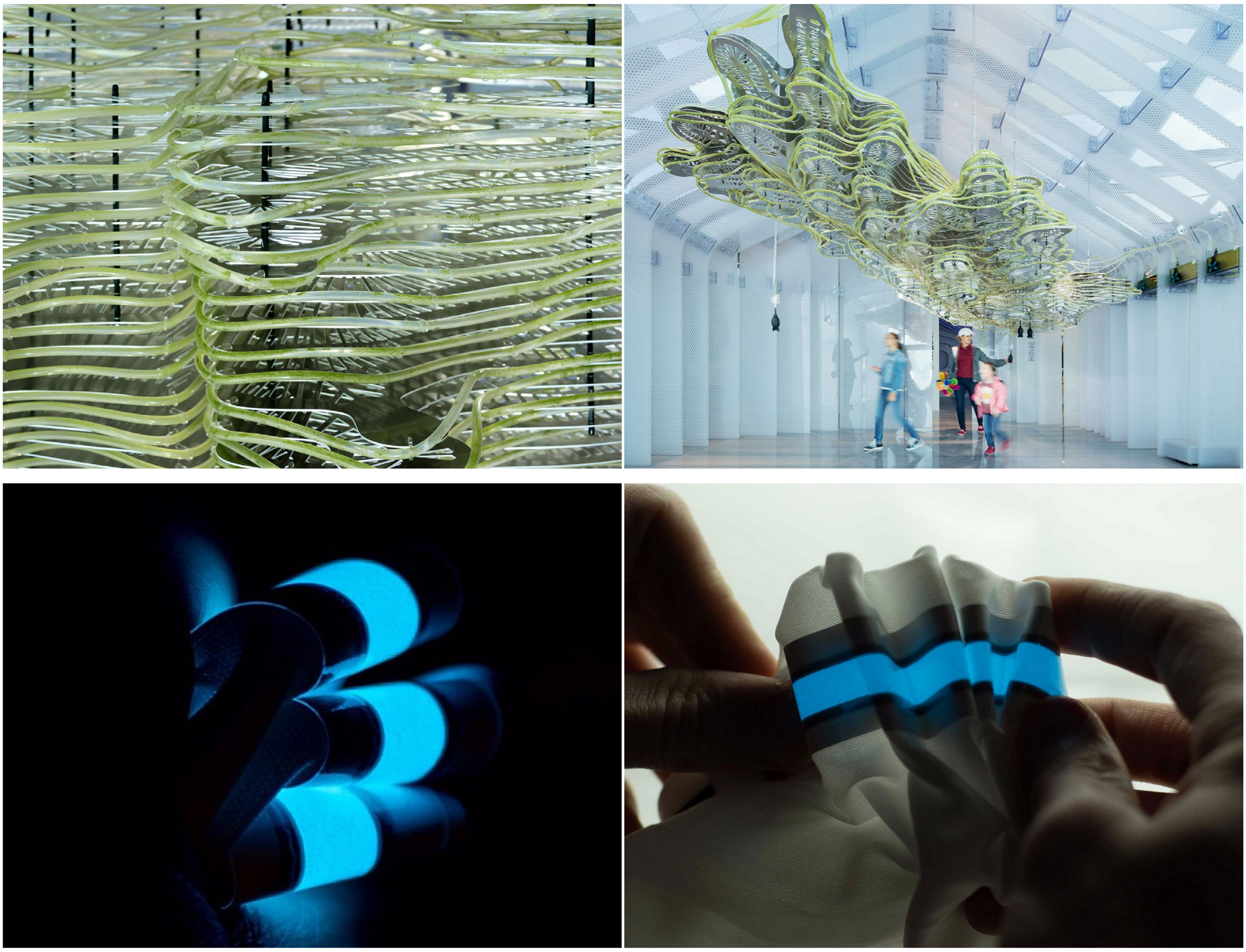


Figure 21. Luminescent Products, on top BIO.tech HUT (n°16), on the bottom VynEL (n°12) reported in Table 4. Source: Naaro for www.ecoLogicStudio.com and www.ellumiglow.com

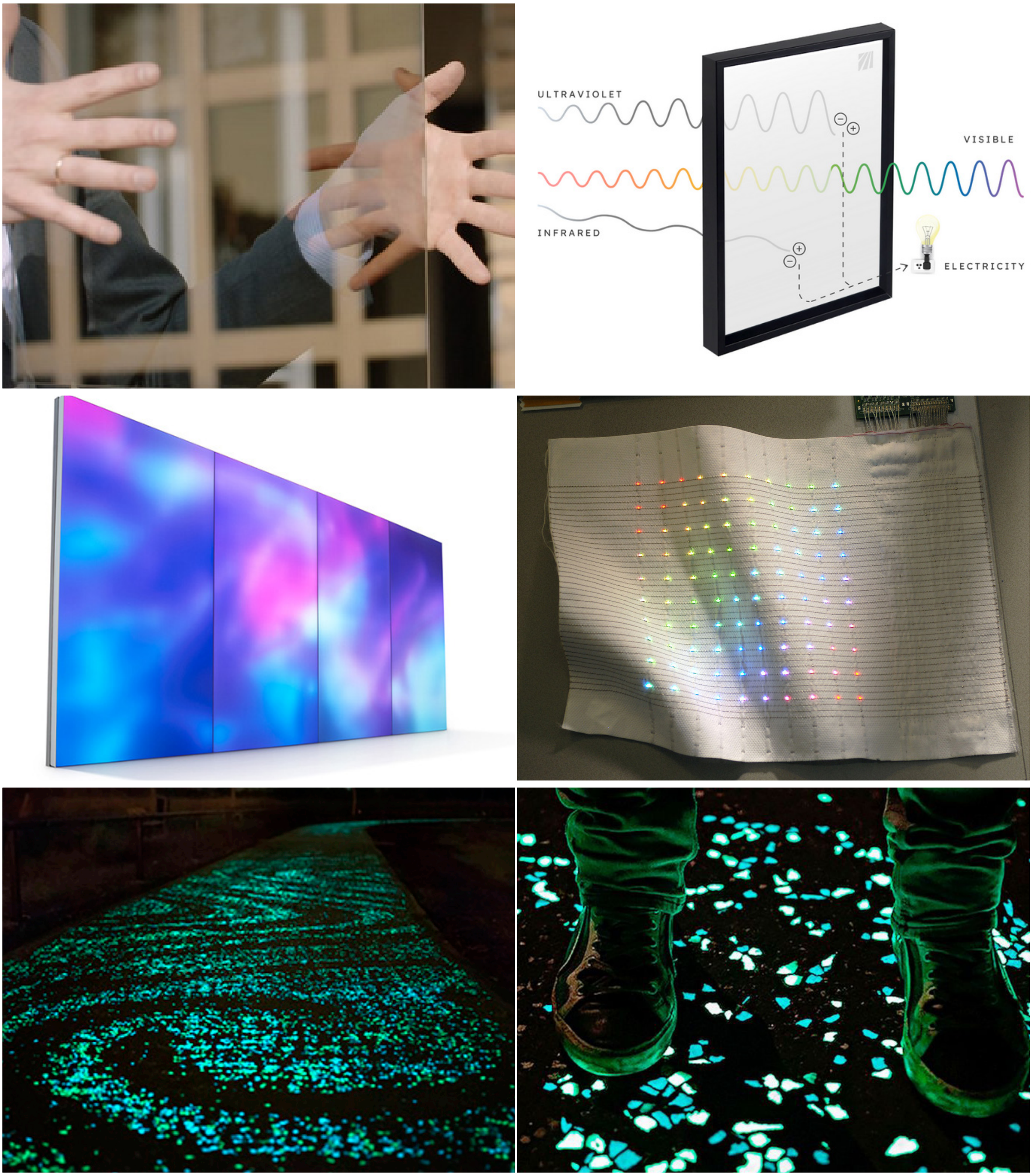


Figure 22. Luminescent Products, on top TLSC (n°1), on the middle Luminous textiles© (n°3), on the bottom Light Emitting Cement (n°6) reported in Table 4. Source: www.ubiquitous.energy.com, www.colorkinetics.com, and Agencia ID/DICYT at www.dicyt.com

Cases are organized according to the applied industry, to observe the variety of luminescent types applied and the state of maturity per each.
Moreover, general characteristics of the evaluated projects are detailed in Table 5, these reply to the characteristics presented in page 55, but are where support material is stated as the main structure on which luminescence has been deposited.

N°	Product or Project	Company or Researcher	Industry	Type of Lum.	Product description	Development status
1	**TLSC** **2011**	Ubiquitous energy	**Energy**	PL	**Transparent** luminescent solar concentrator device that produces **energy through nonvisible light** (UV and IR)	Product
2	**LSP** **2020**	Luminescent Solara	**Energy**	PL	**PL system for parallel generation of electricity** from photovoltaic cells and the otherwise wasted residual heat	Experiment
3	**Luminous Textiles** **2011**	Color Kinetics	**Electronics**	EL	Configurable, high-quality, and unique **lighting system** that integrates multi-colored LEDs seamlessly within beautiful fabric panels **that also soften sound**	Product
4	**Wind-driven Display** **2014**	DGIST	**Electronics**	ML	**Wind-driven deformation displays for roads and countrysides.** Induced by air flow over rods jointed to a vertical plate	Prototype
5	**Printable Hydrogels** **2017**	Nanjing University	**Electronics**	PL	**Elastic, injectable, and healable after damage**. Soft yet moldable hydrogel designed for soft electronics and robotics	Prototype
6	**Light Emitting Cement** **2016**	Universidad Michoacana de San Nicolás de Hidalgo	**Construction**	PL	**Self-luminescent cement-based composite** materials (SLCCM) for environmental protection pavement and smart pavement	Product
7	**ML Paint** **2017**	Kyungpook National University	**Construction**	ML	**Paint** for the visualization of **crack propagation mechanisms in concrete structures**	Prototype
8	**Artificial Leaf (LSC)** **2016**	Eindhoven University of Technology	**Health care**	PL	Leaf-shaped piece able to produce **medicine by photochemical process**	Prototype

N°	Product or Project	Company or Researcher	Industry	Type of Lum.	Product description	Development status
9	**Glucose sensor** **2019**	Jiangsu University	**Health care**	CL	2D metal–organic framework **nanosheet CL-based sensor developed for one-step and rapid detection of glucose in human urine**	Experiment
10	**Fiber-shaped PLEC** **2015**	Shanghai University	**Textile**	EL	**Coaxial sandwiched fiber with symmetrical brightness** for wearable electronic textiles	Product
11	**LUMINOUS MULTITEX** **2017**	Lanex	**Textile**	PL	**Polypropylene multifilament glow-in-the-dark fibre** (threads, cords, braided and twisted ropes)	Product
12	**VynEL** **2017**	Ellumiglow	**Textile**	EL	**Flat and flexible electroluminescent structure able to glow from both sides.** It can be heat bonded, sewed, or glued and is water-resistant	Product
13	**Aerospace impact sensors** **2013**	Indira Kala Sangeet University	**Security**	ML	**"Pain-sensitive skin"** connected to light sensors able to inform about the magnitude and location of the damage in airplanes	Concept
14	**Confidential printing paper** **2019**	Nanjing University	**Security**	PL	**Rewritable and multi-level fluorescent security paper** with the use of water as ink	Prototype
15	**SERVOPRO NOX** **2019**	Servomex	**Security**	CL	**Environmental air monitoring of** NO or NO/NO2/NOx concentrations in industrial gas and vehicle emission applications	Product
16	**BIO.tech HUT** **2017**	ecoLogicStudio	**Agriculture**	BioLum.	**City algae farming.** Unique aesthetic and spatial experience of nature in elegant corporate interiors	Product

Table 4. List of evaluated luminescent cases

N°	Product or Project	Type of Lum.	Constant supply of excitation source	Emission (Activation/ duration)	Reversible change	Continous (C) Multiple (M) Single (S)	Scale/ dimension	Support materials
1	**TLSC** **2011**	PL	Yes	Flourescence	Yes	S	cm - m	Glass
2	**LSP** **2020**	PL	Yes	Flourescence	Yes	S	cm - m	Polymer
3	**Luminous Textiles** **2011**	EL	Yes	Flourescence	Yes	C	cm - m	Natural fibers
4	**Wind-driven Display** **2014**	ML	Yes	Phosphore. Afterglow	Yes	M	m	Polymer
5	**Printable Hydrogels** **2017**	PL	No	Phosphore. Afterglow	Yes	S	mm	Polymer
6	**Light Emitting Cement** **2016**	PL	No	Phosphore. Afterglow	Yes	S	mm - cm	Composite (cement)
7	**ML Paint** **2017**	ML	No	Phosphore. Afterglow	Yes	S	mm - cm	Polymer
8	**Artificial Leaf (LSC)** **2016**	PL	Yes	Phosphore.	Yes	S	cm	Polymer
9	**Glucose sensor** **2019**	CL	No	Phosphore. Afterglow	No	S	mm	Metal
10	**Fiber-shaped PLEC** **2015**	EL	Yes	Flourescence	Yes	S	mm - cm	Metal, Polymer
11	**LUMINOUS MULTITEX** **2017**	PL	No	Phosphore. Afterglow	Yes	S	cm	Polymer
12	**VynEL** **2017**	EL	Yes	Flourescence	Yes	S	cm	Metal, Polymer
13	**Aerospace impact sensors** **2013**	ML	No	Unknown	Yes	S	Unknown	Unknown
14	**Confidential printing paper** **2019**	PL	No	Flourescence	Yes	S	mm - cm	Polymer, Natural fiber
15	**SERVOPRO NOX** **2019**	CL	No	Phosphore. Afterglow	Yes	M	cm	Metal
16	**BIO.tech HUT** **2017**	BioLum.	No	Phosphore. Afterglow	Yes	S	cm - m	Polymer

Table 5. General characteristics of evaluated luminescent cases

The selection was studied to recognize patterns of form and making. The information retrieved was complemented by videos, and images presented by the companies or researchers listed in Table 4 and supported by the studies referenced in Table 5.

From the research it was possible to conclude that in the broad aspect, at least two steps will occur to fabricate luminescence materials (individually or as a chain):

- **phosphors synthesis:** traditionally known as powder metallurgy, uses powders as starting materials. Methods include solid-state reaction, sol-gel, chemical precipitation, combustion. (Lakshmanan, 2012; Sawdea et al. 2019; Rane et al. 2018)

- **phosphor deposition or blend:** Built on or built-up structure in the form of layers, fibers, slabs, etc. Methods include screen printing, layer-by-layer (LBL), electrospinning, diffusion, wet spinning, a self-assembled monolayer (SAM), spin coating, drop-casting, spray pyrolysis (Picco et al. 2016; Wang et al. 2020).

Posterior post-treatments can be included depending on the morphology and purity of the powder or surface according to the desire affordance (e.g. sintering, smoothing the contact in between particles).
After careful analysis of the fabrication of each project, it was possible to group the forms according to possible uses, connected to defined industries.

The following list presents the forms on which luminescence was stated to be incorporated in the material and/or posterior product.
Each form can be generated based on the previous one except for bio-organisms, e.g. thin films are commonly produced by processes on which the material has been provided as a liquid solution, as well as some fiber & filaments, while solid-state lighting corresponds to LEDs, OLEDs, and PLEDs produced by the previous categories listed (from powder to fiber and filaments).

Then, each of these forms can be the material itself, or the raw base to generate a more complex material or product proposal.

Luminescent forms:

- **Powders**
- **Liquid solutions & gels**
- **Thin Films**
- **Fiber & filaments**
- **Solid-state lighting**
- **Bio organism**

While recurrent industries on which the evaluated materials were incorporated consider:

- **Energy**
- **Electronics**
- **Construction**
- **Healthcare**
- **Textiles**
- **Defense & Security**
- **Agriculture**

Table 6 summarizes the information according to the luminescent form, the corresponding cases, and possible uses. This suggestion recognizes that for each of these forms, different luminescent types can be applied, e.g. thin films can be generated as PL, ML, EL, as well as CL, to adjust to different purposes and industries.

Thermoluminescent products have not been included nor evaluated in the selected cases due to a lack of information on products, and possible uses. For this reason, they will not be further mentioned in the studies to come.

Luminescent form	Case n°	Use	Potential industries	Complementing articles
Powders	2, 6, 8 & 15	Pigments	Construction, Energy	Timilsina et al., 2017; Wang et al., 2020
Liquid solutions & gels	5, 7 & 13	Dyes, paints and coatings	Defense & Security, Healthcare	Schneller et al., 2013; Picco et al., 2016; Iyer, 2020
Thin films	1, 4, 9, 12 & 14	Chemo-Biosensors, displays, and solar cells	Healthcare, Energy & Electronics	Zhang et al., 2015; Park et al., 2019; Ding et al., 2019
Fiber & filaments	10 & 11	Textiles and wires	Textiles & Electronics	Guan et al., 2015; Kwon et al., 2020; Iyer, 2020
Solid-state lighting	3	LEDs, OLEDs, and polymer light-emitting diodes (PLED)	Electronics	She et al., 2019
Bio ogranism	16	Farming, dyes, biomimetic environments	Agriculture, Defense & Security	Iyer, 2020

Table 6. Luminescent form proposal

Up next general descriptions of making of this forms are discussed, presenting examples of the cases displayed in Table 4, furhther complemented by referenced articles.

Powders: as the primary form, and pigments

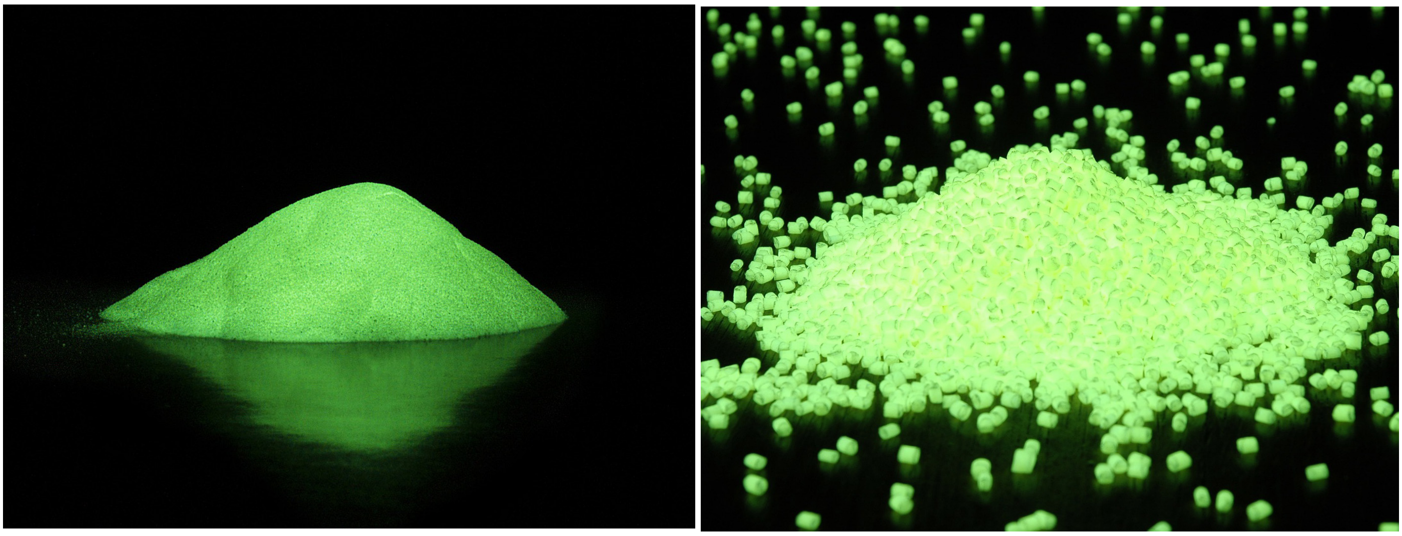


Figure 23. Powders and pellets. Images by Willem Botha and simisi1 from Pixabay

Luminescent powders are the basis for luminescent production, being the general result of synthesis through methods such as solid-state reaction, sol-gel, chemical precipitation, and combustion. The general process for phosphor powders synthesis is schematized in Figure 24.

Phosphor synthesis

Raw materials refinement (matrix, activator, flux)	Blending (blender, ball mill)	Synthesis	Coarse crushing (crusher, ball mill)	Classification (sedimentatio, elutriation, sieving)	Surface treatment (if desired)

Figure 24. Phosphor synthesis process. Source: Yen & Yamamoto, 2006

All of the other forms listed can be generated starting from powder, depending on their quality and dimension (0D to 3D), for which they can be considered as the **primary luminescent form** for industrial fabrication.

They can be acquired in the market generally as pigments or dyes, usually sold to mixture into solutions, producing a variety of luminescent materials. They can be applied to produce from DIY products (e.g. plasticine, soaps, jewelry, toys) to industry-specifics, such as crack sensors, flaw detectors, construction luminescent composites, powder coatings, and radiation meters in medicine (Paredes et al. 2019).

Powders can be dissolved into mediums, generating ligquids and gels, they can be industrially added into polymers, such as PP, PET, ABS, PA, PC, PC-ABS, and Acrylic for manufacturing end products by injection molding, and extrusion, or added to other matrix to generate composite structures, as is the case with case n°6.

'Light-emitting cement' is designed to increase the security of streets at dark hours, while decreasing power consumption in cities when applied at large scale. The product can be generated by introducing 25% luminescent powder (LP) with 10% reflective powder (RP) in medium-size mesh ranges (between 150 to 200) into a matrix of P.W. 42.5 cement. The result is a cement-based composite material (LCCM) with an heterogeneous microstructure and new mechanical properties (i.e. higher compressive strength) (Wang et al. 2020).

Two examples of mesh for the powder form of case n°6 are exhibited in Figure 25.

Figure 25. Two different mesh of luminescent powder doped into cement-based materials, case n°6. Reprinted from Construction and Building Materials, 269, 121267. Wang, W., Sha, A., Lu, Z., Jia, M., Jiang, W., Liu, Z., & Yuan, D. Self-luminescent cement-based composite materials: properties and mechanisms. Copyright (2015), with permission from Elsevier

In a smaller scale, case n°8, 'Artificial Leaf - LSC' mini-factories, able to produce medicine through photochemical processes are made by introducing 0D-nanoparticles of phosphor mixed with Polydimethylsiloxane (PDMS). The leaf shape is cast and curated through techniques of soft-lithography, and print-and-peel (Cambié et al. 2017).

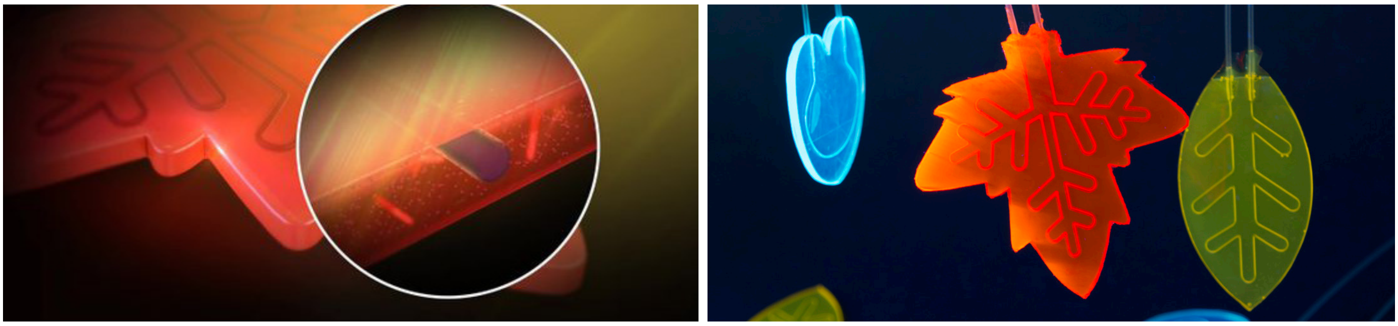


Figure 26. Artificial leaf (LSC), case n° 8. Source: Eindhoven University of Technology

A similar approach, with another function, has been carried for luminescent solar concentrators or LSC for short. These devices able to direct solar radiation into a collecting target, storing and producing energy that can be produced as a slab of PMMA by mixing the solution with 0D luminescent powders until viscous, and then poured into a mold for cooling. This process produces a transparent solid rectangle or square of material. Once integrating PV cells to its edges, it is an electricity-generating replacement for windows.

Another process to produce LSC is through thin films as we will observe further ahead.

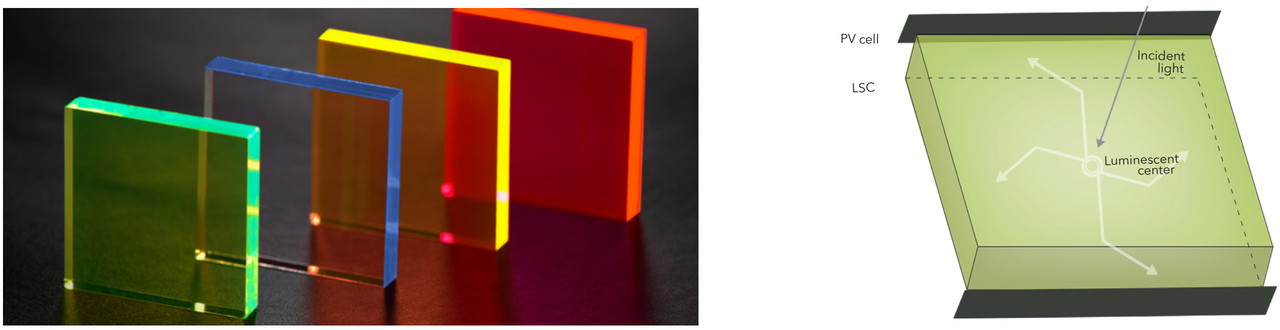


Figure 27. LSC. Source: Ankara Yıldırım Beyazıt University

Liquid solutions & gels: inks, paints, and coatings

Figure 28. Liquid solutions and gels. Images by Vasco Sanchez and Barbara Jackson from Pixabay

Light-emitting liquid solutions and gels can be commonly associated with products as chemiluminescent glowsticks, inks (e.g. DIY clothe dying, UV pens), and paints (e.g. nailpolish).

The general process to produce these forms is by mixing lanthanide ions and ligands in a solvent, resulting in light-emitting fluids. To obtain a gel form add a polymer such as polyethylene glycol, or PEG to the mixture and shake (Chen et al. 2015).
In the gel structure, the dynamic and reversible nature of non-covalent bonds between the polymer chains constitutes the basis for self-healing, allowing recovery from mechanical damage (Li et al. 2019). Other mediums to dissolve the powders include Fiberglass, Polyurethane, Enamel, Lacquer, or Acrylic Emulsions.

These material are able to respond to environmental variations in temperature, pH, chemical sensing, and mechanical agitation. Working as sensors able to report changes through color or brightness emissions. Uses are mainly concentrated in healthcare and defense & security industries.

Case n° 7, 'ML paint' is a proposal where rare-earth luminescent powders have been mixed with optically transparent epoxy resin homogeneously in a ratio of 3:7 at 25 °C. The coating was placed over a surface (in this case cement) to visualize crack initiation and propagation under mechanical fatigue, enabling to characterize the long-term integrity of various concrete structures (Timilsina et al. 2017).

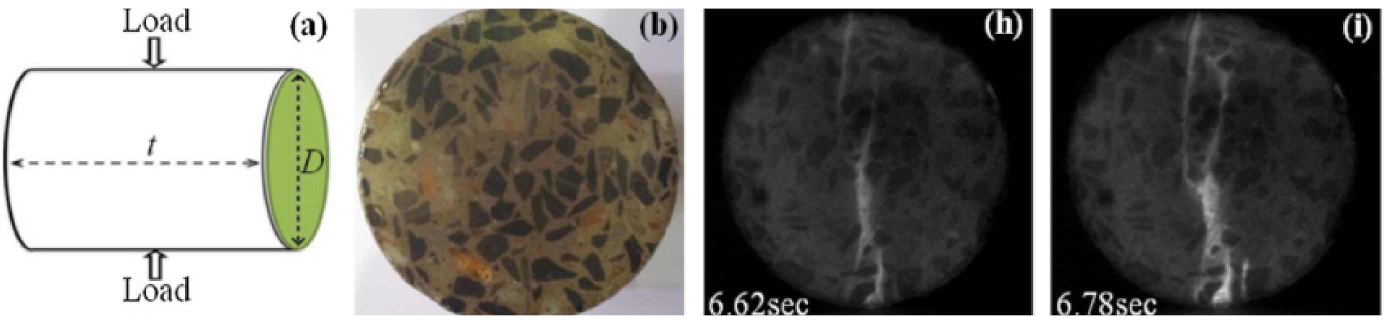


Figure 29. Sequential ML images recorded by a digital imaging system. (a) Schematic diagram of splitting test, (b) ML paint applied on the flat surface of the specimen, and (h–i) ML images of crack propagation in a splitting test of a concrete. Reprinted from International Journal of Fatigue, 101. Timilsina, S., Bashnet, R., Kim, S. H., Lee, K. H., & Kim, J. S. A life-time reproducible mechano-luminescent paint for the visualization of crack propagation mechanisms in concrete structures, 75-79. Copyright (2017), with permission from Elsevier

A similar proposal on a larger scale is presented in case n° 15 'paint sensitive skin for aerospace impact sensors' where a coating emits signals caught by sensors that can detect the location and severeness of the damage through the brightness of the emission. The self-healing properties of the material could be especially important due to the environment exposure of the context.

To illustrate the previous idea, Figure 30 presents images of experiments to produce fluorescent ML liquids and gels, carried in the MIT energy initiative. This proposals, is under investigation to generate sensors for measuring variations in pressure and other parameters in flowing fluids.

Figure 30. Mixture and range of colors in liquids and gels. Source: Stuart Darsch and Pangkuan Chen

Thin Films: singular layers, coatings, and sandwiched structures

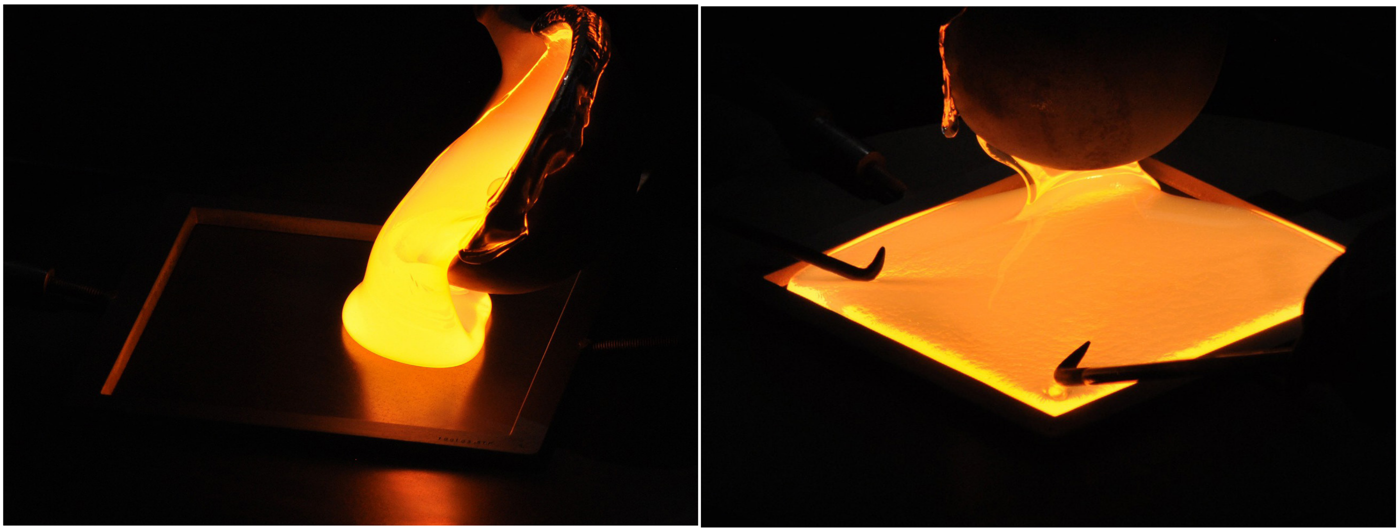


Figure 31. Thin Films. Images by Birderswiss_Photography from Pixabay

Thin-film deposition of material comprehends from fractions of a nanometer to several micrometers in thickness. Luminescent thin films characterize for proportionate multi-functional optical properties based on high transparency.

Either uncolored or in shades, the 2D form can be generated as a singular layer -with one axis of flexibility, perpendicular to the film-, placed on top of structures as coatings (e.g. polymers, glass, or even wood) or sandwiched at the center of other materials through methods like drop-casting, spin-coating, layer-by-layer, digital printing, electrospinning, and screen printing. They are used in a wide variety of industries to generate from displays, screens, solar cells, to chemo/biosensors.
This form allows thin, flexible, lightweight results which can vary depending on the selected materials for each layer (Guan et al. 2015; Li et al. 2020; Kwon et al. 2020).

Case n° 4 'Wind-driven display' corresponds to an example of a singular layer film with a range between 450 - 500 μm of thickness. A paste prepared by mixing the luminescent powder with PDMS and poured onto a glass plate, cured at 70 °C for 30 minutes. The layer is then sliced to form rods that are posteriorly attached to a vertical plate. The stress applied to the connection area by the wind flow generates a vibration that emits light due to ML (Jeong et al. 2014).

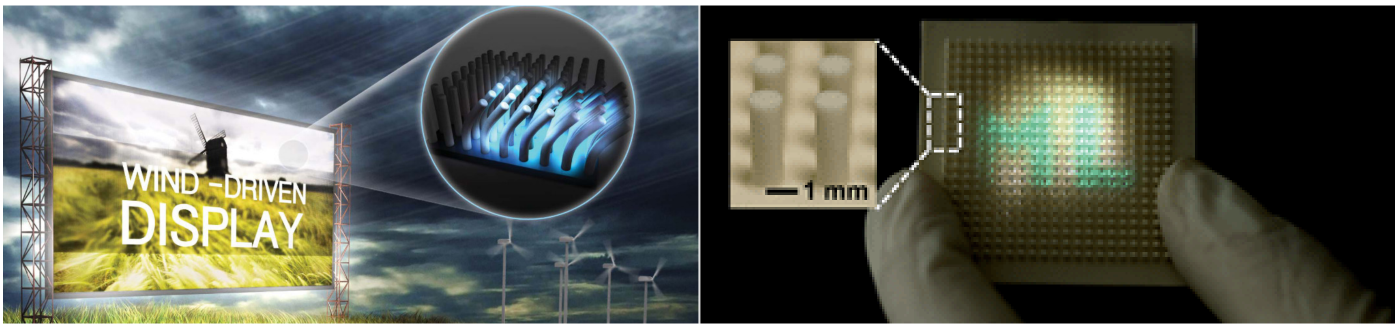


Figure 32. Wind-driven white mechanoluminescence display. Images reprinted from Energy Environ. Sci.,2014, 7, 3338. Article is licensed under a Creative Commons Attribution 3.0 Unported License

Case n°1 'TLSC' (top images in Figure 22) corresponds to a transparent coating deposited directly onto the glass during the glass manufacturing process, the process enables to obtain transparency between 40-70%. The glass is posteriorly framed with hidden PV cells, which allow storage and generate energy.

A recent case of luminescent thin film coating has been registered to manufacture multifunctional flexible wood film by chemically infiltrating luminescent nanoparticles coated by a hydrophobic soluction via chemical vapor deposition. The result is a mechanically strong, flexible, and hydrophobic yet polymer matrix-free material (Fu et al. 2020).

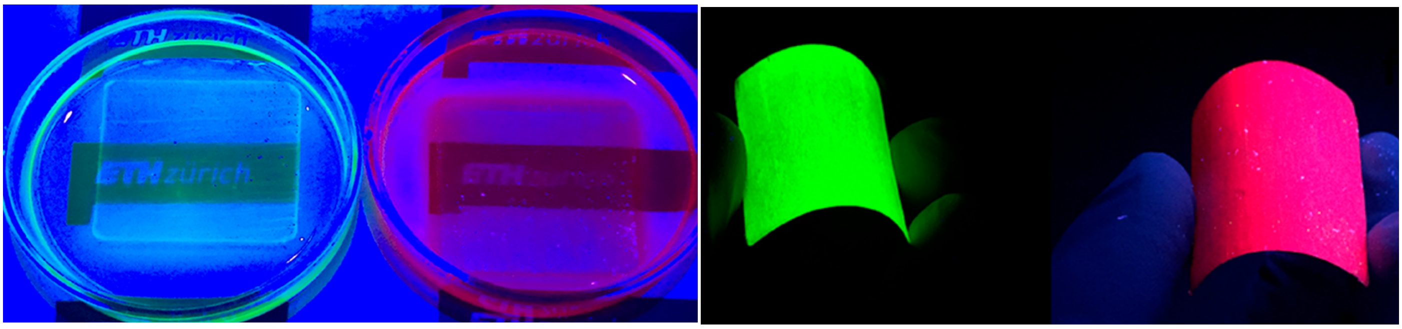


Figure 33. PL solution infiltrated over wood film. Reprinted (adapted) with permission from American Chemical Society, 14(10). Fu, Q., Tu, K., Goldhahn, C., Keplinger, T., Adobes-Vidal, M., Sorieul, M., & Burgert, I. Luminescent and Hydrophobic Wood Films as Optical Lighting Materials. 13775-13783. Copyright (2020)

Examples of sandwiched structures made from thin layers are described in cases n° 12 'VynEL' and n° 14 'Confidential printing paper'.

Electroluminescent products such as VynEL, a flexible strip that can be attached to several textiles and surfaces, are produced by layering conductive materials above and beneath a phosphor thin film deposition.

A standard sequence for the production of EL strip structures considers from top to bottom a layer of polystyrene sulfonate (PEDOT) as the cathode, followed by the thin film of the desired phosphor deposited by methods such as drop-casting, spin-coating, layer-by-layer, or digital printing over a polymer or glass, depending on the needed flexibility (i.e. support structure).
The bottom layer usually corresponds to indium tin oxide (ITO) as anode, a transparent conductive layer connected to a power source.

Other examples of EL strips plus the an illustration of the general sequence previously described is presented in Figure 34.

Figure 34. EL strips. Image by Light Tape UK at creativecommons.org

Analog to the EL stip structure the same notion is applied for case n°14. To generate rewritable and multi-level security printing paper a series of polymer layers coated on top of a sheet. The procedure uses water as ink and displays the information under UV light and erase once heat is provided (She et al. 2019).
A top and bottom layer of poly(ethylene glycol)-block-poly(propylene glycol)-block-poly(ethylene glycol) (PEG-PPG-PEG) sandwiched a PL thin film incorporated over an equal to the previous polymer layer. All the previous coated the support structure of filter paper.

Fiber & filaments: wrapped and singular

Figure 35. Fiber and filaments. Source: 'Playing with el wire' by Mavroudis Kostas at search.creativecommons.org

The cylindrical-shaped form of light is characterized by promoting ultra flexibility -in the plane perpendicular to thein fiber- as well as excellent conformability, besides uniform emission with a coverage of 360°. This particular form has been mainly developed for its use under activation of electric power sources (i.e. electroluminescent) for fibertronics (i.e. wearable electronics), nonetheless, several outcomes and investigations are being carried due to form properties.

Case n° 10 demonstrates the first fiber-shaped, solution-processed PLEC. The form consists of two air-stable electrodes and a single active layer containing a 'conjugated polymer' a light emitter, an ionic conductor, and a dissolved salt. The luminescent fiber was generated by wrapping a stainless steel wire with a ZnO nanoparticle layer, an EL polymer active layer, topped with a sheet of aligned carbon nanotube (CNT). The manufacturing was developed by dip-coating (ZnO and EL layers) and wrapping processes (Zhang et al. 2015; Kwon et al. 2020).

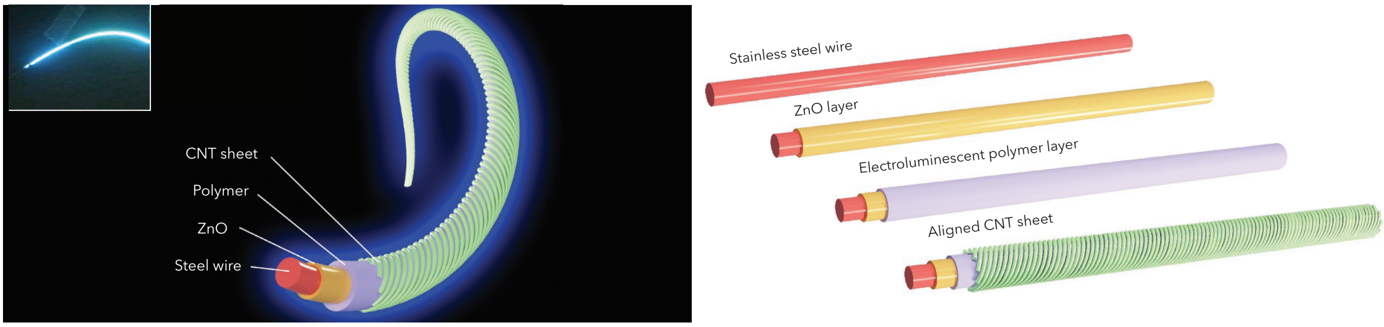


Figure 36. Schematic of fabrication of a fiber-shaped PLEC, case n° 10. Adapted from Nature Photonics 9(4). Zhang, Z., Guo, K., Li, Y., Li, X., Guan, G., Li, H., Luo, Y., Zhao, F., Zhang, Q., Wei, B., Pei, Q., & Peng, H. (2015). A color-tunable, wearable fiber-shaped polymer light-emitting electrochemical cell. 233–238. Copyright 2015, Springer Nature

This is one of the most iconic luminescent fiber shapes stated up to this point.

Other methods to produce filaments include the 'ML fiber' consisting of a surface-treated cross-shaped fiber frame, topped by three coating layers (a primer for bonding increase, followed by a mixture of PDMS+ZnS for luminescent properties, covered by a silicon adhesive layer of Si).

This approach of ML luminescent fiber is highly compatible with wearable technologies as the activation source for ML can be generated by human motion such as bending and stretching (Jeong et al. 2017). Figure 37 exemplifies this fabrication method.

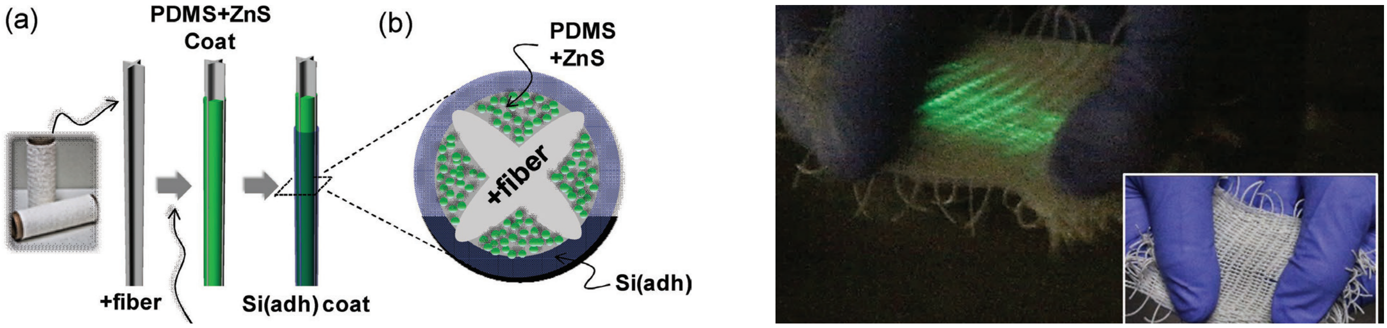


Figure 37. (a) Schematic illustration of ML fiber fabrication process (b) Cross-sectioned ML fiber (c) Photograph of functional fiber. Adapted with permission from Advanced Sustainable Systems 1(12). Jeong, S. M., Song, S., Seo, H. J., Choi, W. M., Hwang, S. H., Lee, S. G., & Lim, S. K. Battery free, human motion powered light emitting fabric: mechanoluminescent textile. Copyright 2017, Wiley-VCH

Another approach to produce luminescent filaments is presented by case n° 11 'LUMINOUS MULTITEX'. For this material, the process consists of adding PL colorant masterbatches to the matrix polymer (in the feed hopper) which is then extruded by the conventional melt-spinning method (see next Figure) (Hufenus et al. 2020).

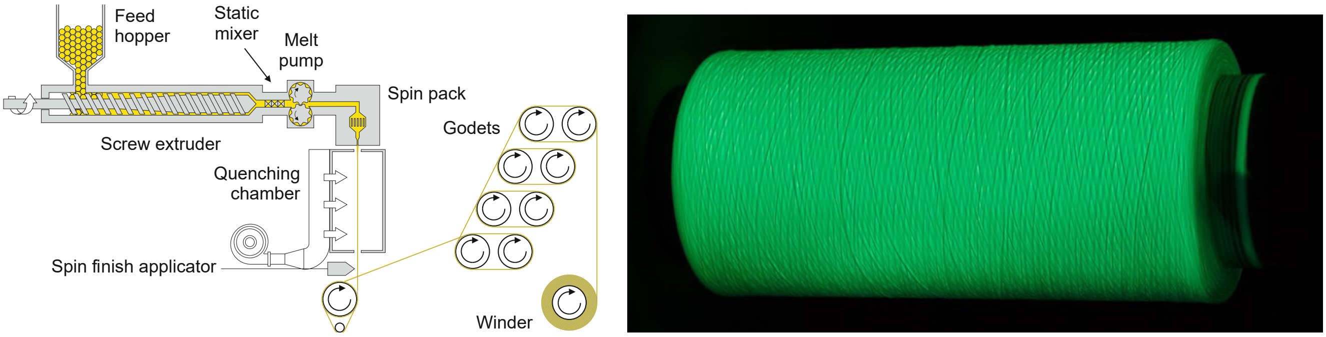
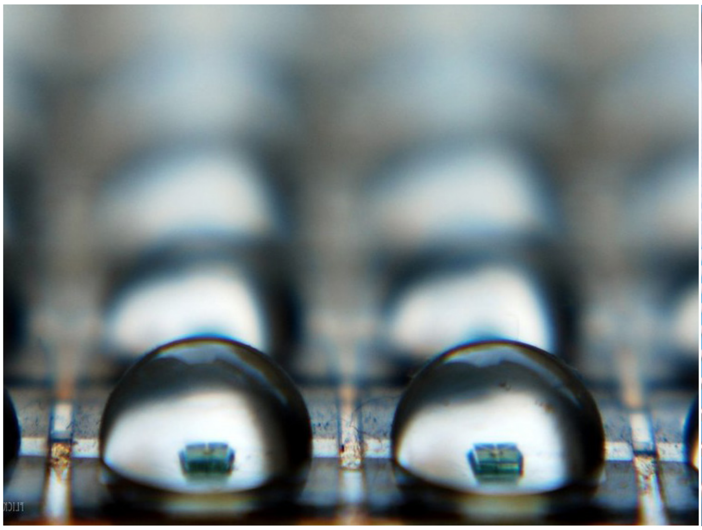


Figure 38. Illustration of polymeric making process and result. Reprinted from Melt-spun fibers for textile applications, under open-access license

A fourth approach to generate luminescent filaments is through intervening natural fiber making. This process can be done in three different ways, internal intervention, process alterations, or external post-treatments.
Let's take the production of silk and silkworms as the example, for this case to generate functional filaments modification can be provided in the silkworms' gene, it's diet, or by processing the silk after it is produced, all of them to generate a fiber luminescent outcome (Tansil et al. 2012).

This last option will be further reviewed in the bio organism entry.

Solid-state lighting: LED, OLED, PLED



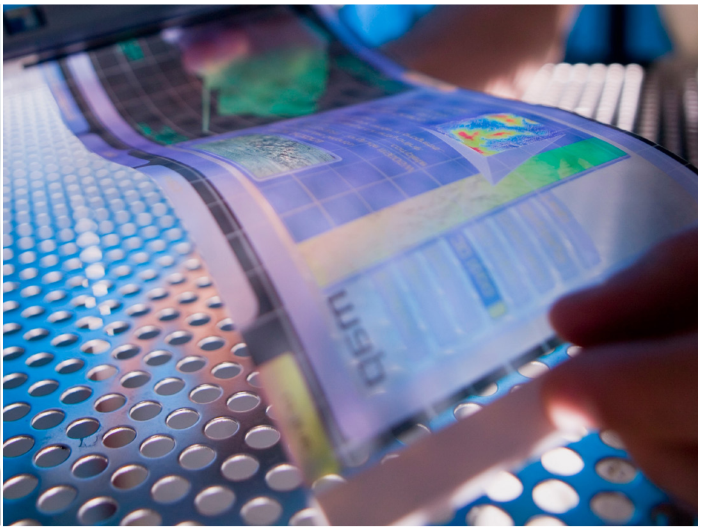


Figure 39. Solid-state lighting. Source: 'Flexible display' by U.S. Army RDECOM at commons.wikimedia.org, and 'LEDs before singulation' by ...-Wink-... at search.creativecommons.org

Since the mid-nineties, three particular forms have revolutionized energy efficiency and smart lighting. Corresponding to the electroluminescent type, LED, OLED, and PLEDs, also known as Solid State Lighting or SSL characterize for providing compact, cost-effective, energy-efficient, UV-free, and environmentally friendly solutions (as they don't present mercury), with a discrete emission viewing angle beneath 170°. (Nakamura, 2017). Moreover, they stand out due to their capacity to provide specific desired colors, impacting in the user-consumer's perception.
Their superior qualities include their extensive lifetime, their ability to create visible light with virtually no heat or energy dissipation, as well as the fact that they consume less power, for which they can be acquired to improve or create new uses, materials, or products.

Light-emitting diodes or LEDs are created from crystalline semiconductor materials (i.e. wafers) with added impurities. One of the layers of semiconductor material will have an excess of electrons, one layer will be depleted of them (i.e. P-N junction). Impurities are incorporated into the semiconductors generally by liquid or vapor phase. Posteriorly metal contacts are included according to affordance. To finalize, a plastic case made from epoxy resin is placed to protect the system from both vibration and shock as well as to improve the brightness of the light energy, and wires are attached to allow the connection.

Available in several shapes, sizes, and colors, either as discrete components with emissions in one color (red, orange, amber. green, blue, yellow, and white), bi-color, tri-color, together as clusters, strips, or even segment displays and high-intensity light source products.

Figure 40. An array of LEDs with different sizes, shapes, and colors. Source: 'LEDs in different casings.' by Afrank99 at commons.wikimedia.org

Many products are generated today taking advantage of the characteristics of LEDs.
Case n° 3, 'Luminous textiles©' is the clearest example of a product design for the digital era. It not only exploits visual stimulation by knitting LEDs in between the fabric, seamlessly hiding their presence while providing color and brightness shifts (see Figure 22, middle image) but it also plays with the acoustics as it helps diminish noise thanks to the properties of the fabric itself.
LEDs are a highly recommendable option for designs that require continuos-reversible change, with tunable color options where flexibility is not a requirement.

In the case that flexibility is required, a better option is OLEDs.
OLEDs are made from organic, carbon-based materials, comprised of a system of several very thin layers of various materials situated between electrode layers. Their fabrication follows the same principle displayed in Figure 34, an anode that attracts electrons, a cathode that gives electrons, a substrate that forms the framework, and organic layers in between, divided into the hole-transport layer (HTL), hole-injection layer (HIL), electron-transport layer (ETL), and electron-injection layer (EIL).
They can be printed onto any medium, generally by vacuum vapor depositions or solution techniques, allowing light-weight designs and flexible screens (their main use) that can be bent or rolled (particularly glass, plastics, or metal foils) (Nakamura, 2017; Pardo et al. 2000).

The other class of organic light-emitting diodes corresponds to PLEDs (polymer light-emitting diodes).
PLEDs are the response to fight complexities of fabrication with OLEDs (i.e. insufficient fine-dispersion of dopant in the host material, phase separation, cost of fabrication), by incorporating phosphorescent guest into polymers. They have faster display responses (activation time), are even thinner while providing flexibility.
Disadvantages regarding both organic diode types are related to their need for very good sealing, as the compounds can get damaged by water.

Both OLEDs and PLEDs are a source of surface emission, enabling the devices where they are applied to have a viewing angle of around 170 degrees, with one axis of flexibility (Nakamura, 2017).

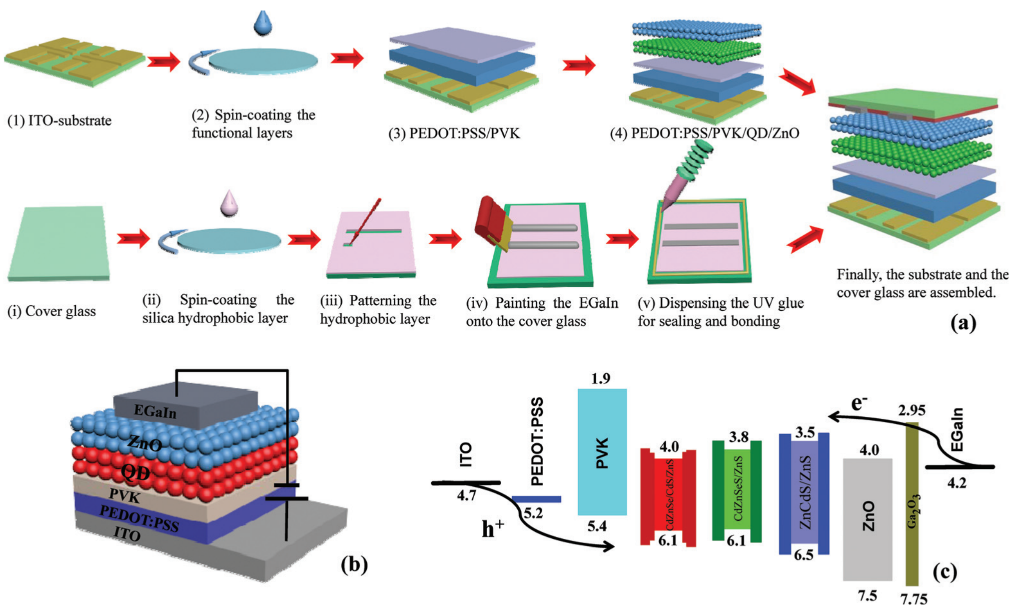


Figure 41. (a) Fabrication of PLED, (b) Schematic diagram of device set-up and (c) Energy band level diagram of *the* vacuum-free-processed PLEDs. Reprinted from Peng, H., Jiang, Y., & Chen, S. (2016). Efficient vacuum-free-processed quantum dot light-emitting diodes with printable liquid metal cathodes. Nanoscale, 8(41), 17765–17773. with permission The Royal Society of Chemistry

Bio organisms:

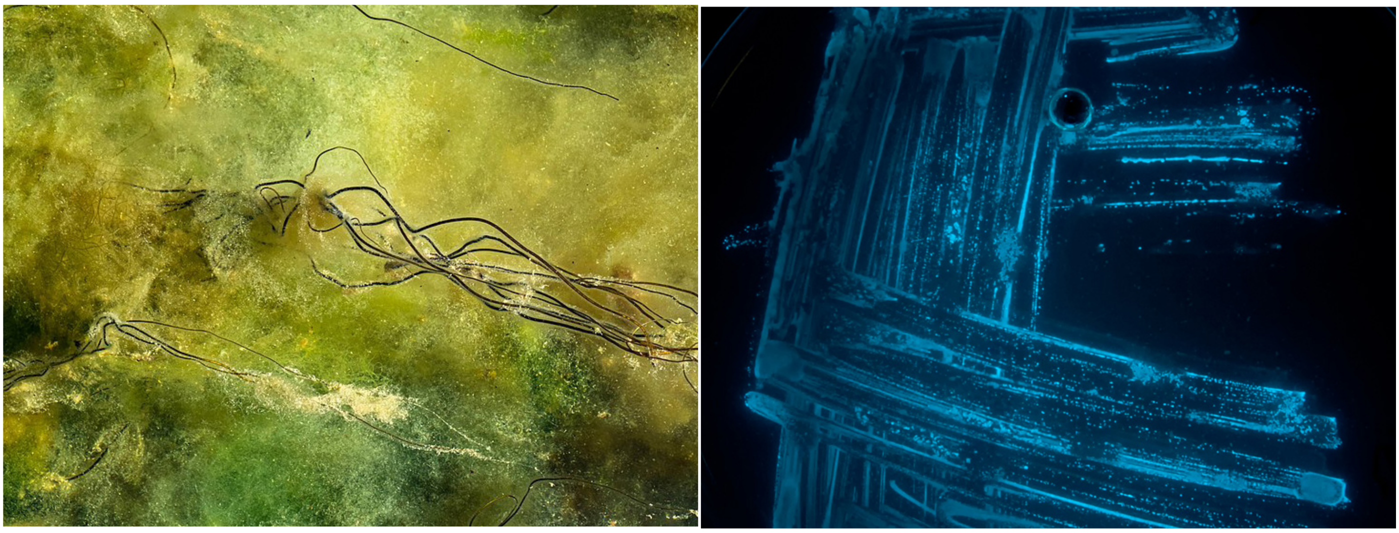


Figure 42. Bio organisms. Image listed as public domain by W.carter at commons.wikimedia.org, and 'Glow in the dark bacteria (Photobacterium phosphoreum)' by Arne Kuilman at search.creativecommons.org

Aiming to combine notions of biomimicry, sustainable, eco-friendly solutions, researchers have explored the potentials of the use of luminescence phenomena existing in nature.

This focus explores organisms with bioluminescent and photoluminescent responses. Through analyzing their working principle proposals branch into either incorporate organisms directly onto the design or alter the organism on some level, generating luminescent response at a large scale.

Case n° 16 'BIO.tech HUT' is an example of the first approach (see Figure 21, top images). Case n° 16 'BIO. tech HUT' is an example of the first approach (see Figure 21, top images). Orchestrated as a lab, the HUT is a space where micro-organisms are domesticated and engineered into artificial cultivation environments. All possible advantages are taking into consideration in this design as they separated different rooms to exploit the qualities of bioluminescence emission. On the one hand, there is a space with a dark-calming environment illuminated only by the emission of the algae, used for meditation and relaxation, while other areas are destined to grow phototropic micro-organisms that use photosynthesis to generate biomass and oxygen while absorbing carbon dioxide, which is posteriorly transformed in food and electricity.

Cases as such aim to take the organism and introduce it into an environment that utilizes the luminescent benefits of it generally encapsulated in a liquid medium.
Another example with a more simple outcome is presented by the company Pyrofarms, which sells 'lamps' that work by the presence of PyroDinos (phytoplankton) inside a sphere full of saltwater. By changing the day-night cycle of the plankton it is possible to obtain light emission from them at night time, which gets activated as a defense mechanism when their ambient is disturbed by shaking or moving the object.

Other uses of bio-organisms are usually related to their incorporation into textiles in one of three methods: post-treatments, genetic modifications, or intrinsical coloring.

Iyer (2020) recently presented methods to generate luminescent textiles by incorporating immobilized Vibrio (photobacterium) fischeri luciferase enzyme into nonwoven textiles by applying surface treatments to the samples, such as air atmospheric plasma, and inkjet printing.

With the same aim, studies carried by Tansil et al. (2012) have displayed a genetic engineering approach by inserted the genes of fluorescent proteins into domesticated silkworms in attempts to explore the use of silkworms as bioreactors for the production of luminescent cocoons. While following an intrinsic path, color can be altered in the silk by feeding silkworms with a dye-containing diet (e.g. fluorescein sodium, sulfoRhodamine 101, Rhodamine 116, Rhodamine 110, acridine orange, Rhodamine 101, Rhodamine B), providing innovations by realizing that alterations in the mechanical properties can also be achieved by this method.

The three different options to provided changes are shown in Figure 43.

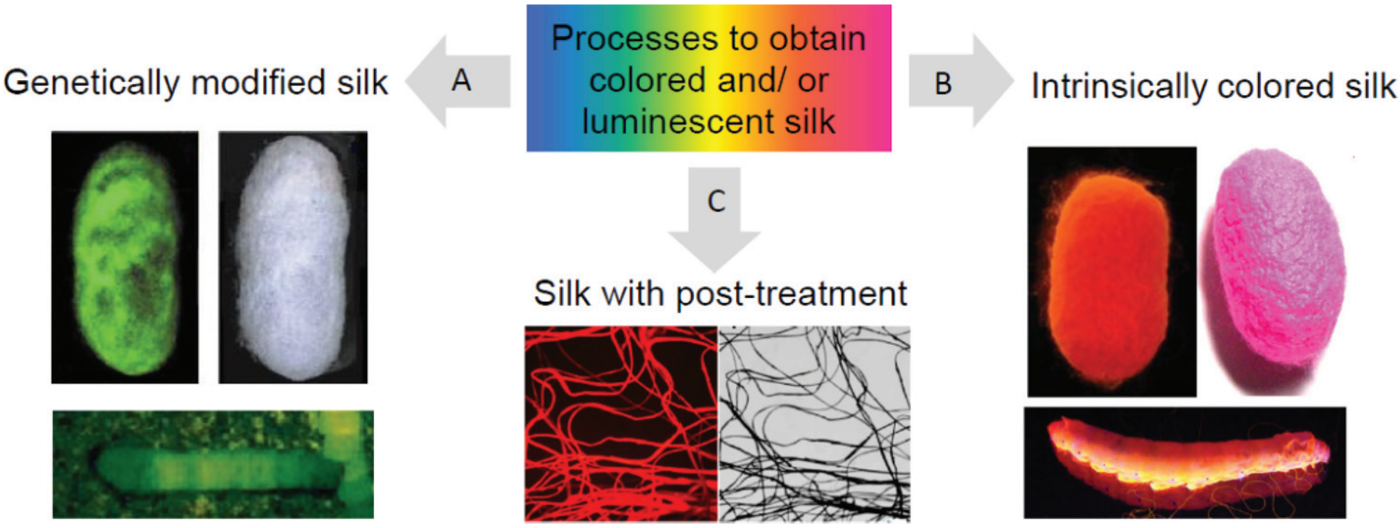


Figure 43. Various ways of producing colored and luminescent silk. Reproduced with permission Tansil, N. C., Koh, L. D., & Han, M. Y. (2012). Functional silk: Colored and luminescent. Advanced Materials, 24(11), 1388–1397. Copyright 2012, Wiley, 2000, Nature Publishing Group and 2008, IEEE

With the analysis of the possible luminescent forms, a couple of indicators have been highly remarked, becoming complementary characteristics that could help in the definition and selection of luminescent materials.

These are:

- Flexibility - Rigidity
- Thinnes - Robustness
- Direction of light-spread (i.e. point source, surface source, all directions)

These indicators, as well as the ones presented in Figure 18, serve as general guidance as they are concluded by qualitative factors. Figure 44 present the summary of the light forms, including also the materials stated to be used for each form, listed as follows:

Luminescent form		Observed Types	Thiness	Flexibility	Direction of light-spread	Support material
Powders		CL, PL, TL, ML	Variable	○	Point source (under 170°)	Polymers, Composites (concretes)
Liquid solutions & gels		CL, PL, ML	⊚	⊚	Surface source All directions (hydrogels)	Polymers
Thin films		CL, PL, EL	⊚	◎	Surface source (around 170°)	Glass, polymers, metal foils, natural materials (wood)
Fiber & filaments		PL, ML, EL	◎	⊚	All directions (360°)	Metal, polymers, natural fibers
Solid-state lighting	LED	EL	○	○	Point source (LED) Surface source (OLED -PLED)	Glass, polymers, metal foils, natural fibers
	OLED		⊚	◎		
	PLED		⊚	◎		
Bio ogranism		Biolumin, PL	Variable	⊚	All directions Surface source (post treatments)	Natural fibers, polymers
LEGEND					less ○ ◎ ⊚ more	

Figure 44. Summary of luminescent forms characteristics

To illustrate the different luminescent forms studied Figure 45 presents a simplified scheme.

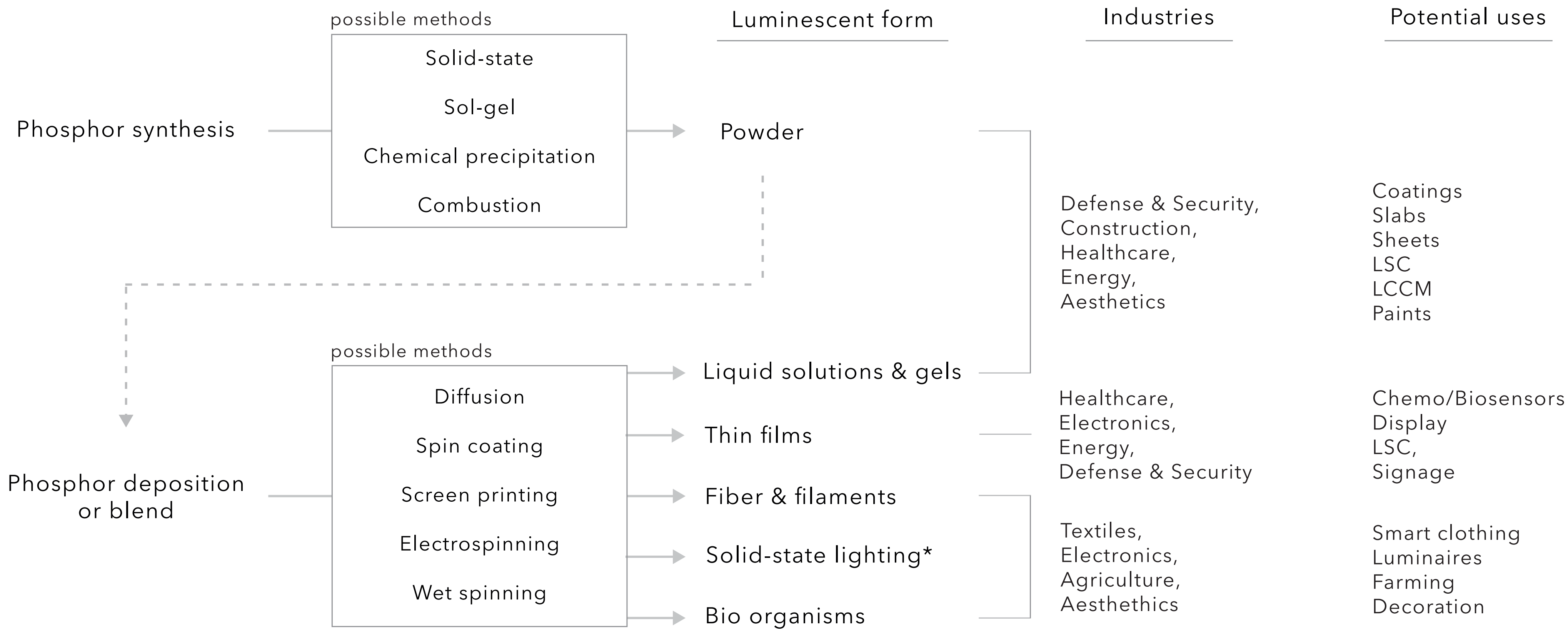


Figure 45. Scheme of luminescent forms, industries and potential uses

2.3.4 Luminescence applied in product design

'The potentials of materials do not present themselves to the designer as 'given'; they are rather constructed through situated actions and reflections'
Schön, 1983

Through the previous sections, we have studied indicators, types, and forms that help define and distinguish luminescent materials, replying mainly to the product's formal aspects and performance. Moreover, especially due to the sensorial language provided by the dynamism of luminescent materials, this aspect must be incorporated into the analysis.

Light is the physical phenomenon most responsible for our perception of the world, it affects our interpretation of shapes, the emotions we elicit, affecting all of our patterns. Light carries information, it transmits messages as demonstrated by Ham and Midden (2010) *'conveying information through light is more effective than numerical feedback'*.
Lighting feedback can have a stronger persuasive effect than alphanumeric feedback (approximately 27%).

Studies such as the one carried by Yang et al. (2016) where sliced apples and red bell peppers were presented under five different colors of light: white, yellow, green, blue, and red, aimed to determine whether ambient light colors affect consumers' willingness to eat. Results demonstrated that light colors (such as yellow) modulate consumers' hedonic impressions of foods, affecting even the flavor intensity.
For years studies centered in the psychology of color have demonstrated that qualities of light related to color Brightness, Hue, and Saturation (i.e. luminous efficiency, color or shade, and intensity of color) have a direct impact on our decisions. For example, it has been shown that warm, soft, or dim light leads patrons to spend more time and money in dining establishments (Wansink 2004; Gal et al. 2007).
The previous refreshes the notion that to know and distinguish properties of light can help us recognize the patterns they can generate in users, amplifying or diminishing the desired experience of products.

As they don't produce heat dissipation, the primary and main organ with which luminescent materials communicate is the eye. How light express upon an artifact can affect our interaction, making it relevant to consider properties that can help us define the outcome we desire to be.

Visual sensory properties have been studied and proposed by many authors (Karana et al. 2009; Zuo, 2010; Vergara et al. 2011; Haug, 2016). But have been recently presented a list of four attributes defined under an intensity range by Piselli et al. (2018):

- Glossiness: Shiny - Matte
- Surface evenness: Uniform - Non-uniform
- Color intensity: Intense - Light
- Transparency: Transparent - Opaque

This group has been selected as a base response as they reply to aspects that play a key role in the qualities of light and is complemented by indicators observed in the previous section, such as:

- Luminous efficiency
- Type of change (single, multiple, continuous)
- Direction of light-spread (point source, surface source, all directions)

With a spectrum of variables that enable the definition of luminescent materials in functional-hedonic means, it is possible to recognize the potentialities they present for product design.

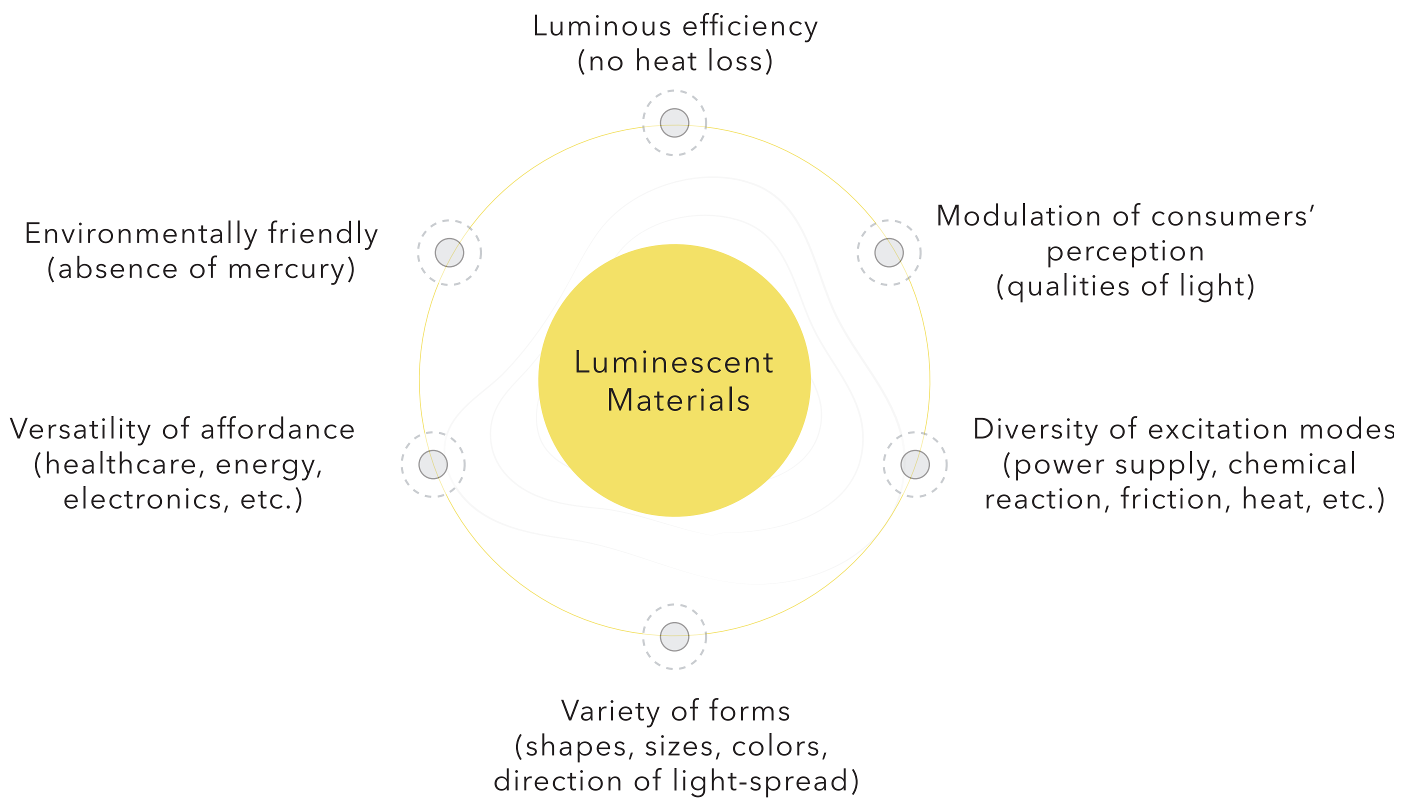


Figure 46. Potentialities and impact of luminescent materials

Moreover, it provides the very first approach of how these materials could be disseminated to facilitate their selection under digital era parameters.

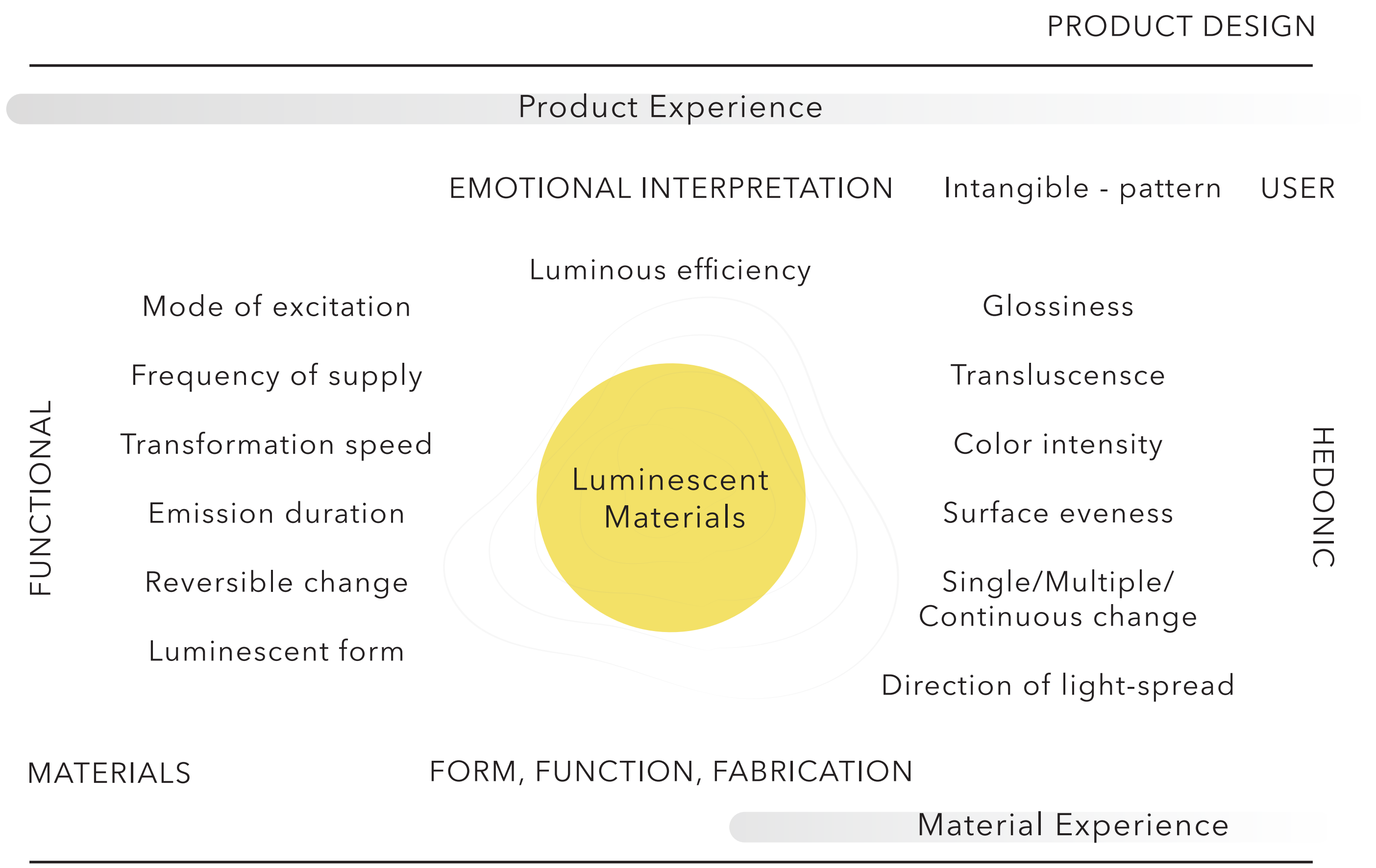


Figure 47. Variables of luminescent materials for product design selection under the digital era parameters

This first set of properties enables to facilitate access and explanation of luminescent materials.

The following chapter focuses on the structure of the process to consider and evaluate the suitability of a material for a defined context, known as material selection.
This final layer will provide the basis to define how the study will proceed, the design goals, and the methods to obtain them.

Chapter summary

Materials can be categorized according to the response they provide to an energetic stimulus, generating a dialogue with the user through interaction. The categories names' are Inactive, Reactive, and Proactive.

Reactive and Proactive materials, also known as ICS materials, deploy dynamic sensory language, variating how our organs perceive them during the interaction, this is their main potentiality and differentiation.

In the Reactive kind, we can encounter **Luminescent materials, capable of emitting light as a response to an energetic stimulus** such as chemical reactions, electromagnetic fields, light stimulation, to name a few.
Their efficiency, and versatility, both in form and adaptability to several environments and industries positions them as a must knowledge for product designers of the field.

This chapter evaluated properties that distinguish their performance (e.g. mode of excitation, transformation speed, emission duration, etc.) as well as their visual qualities (e.g. color intensity, type of change, the direction of light-spread, etc.) aiming to reply to the parameters for evaluation of materials in product design in the digital era, recognizing that their selection can generate patterns of response in users, enabling to generate desired experiences.

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Chapter 3:

Material selection

‘Designers have to understand their role as creating the defining parameters in a digital environment for fluid products.’

Dean & Loy, 2020

3. Material selection

The ease of communication characteristic of the digital era has also brought a universal rise in product demands and market competition.
With the era's criteria, the pressure to accomplish products able to balance functionality, personality, performance, efficiency, and environmental awareness has increased (Prendeville et al., 2012, Beka, 2016, Tian et al. 2019, Dean & Loy, 2020).
The task to filter and prioritize information is one of the jobs of product designers, nonetheless, it can be a time consuming-complex job, for which tools have been developed.

In product design, as well as in several disciplines, the selection of materials is treated as a **system of classification** that works like a funnel. Ashby and Johnson (2010), describe the method as a tool that should:

'(a) capture and store material, process, and product information, organizing it in a way that allows rapid retrieval
(b) present the same information in a creative format, and,
(c) allow browsing, retrieval, and combination of 'bits' of information about materials, processes, and the products they create.'

Complementing the list, the method should also fit the time frame, as each era has not only implemented new resources to work with but also new perspectives.

> *'Not only are people consuming materials more rapidly but also they are using an increasing diversity.'*
> *Karana et al. 2008*

Karana's declaration can be disseminated in various aspects, consumer behavior, programmed obsolescence, linear/circular economy; No matter what the approach is, the general picture is that **demands are the evolution of available resources combined with human needs**, the reflex of the relevant influences (external - resource recognition), and constraints (internal - defined by the practitioner) of a determined period (Prendeville et al. 2012).

Since their inception, **formal proposals of selection models have prevailed on engineering -medium-term- point of view, centered on the technical, economical, and manufacturing aspects of the material profile**, appealing to its functionality while in use.
As stated in Chapter 1, the movement to consider materials as a source of meaning is recent, a wave of this particular era.
Translated in the selection method, the desire is to articulate as many layers as possible, or as Piselli (2018) has suggested, to obtain:
'a method of selection that allows technical and design specifications to be integrated, to increase material choice agreement.'

Then, the material selection objective is to recognize requirements and guide the selection to the best-suited material for the context.

Corresponding to the evolution of parameters for material selection in the field, described in Chapter 1, Table 7 illustrates some of the most relevant models proposed throughout the years, under the perspective of 2020-2021 material experience parameters.

Source:
Karana, E., Hekkert, P., & Kandachar, P. (2008). Material considerations in product design: A survey on crucial material aspects used by product designers.
Piselli, A., Baxter, W., Simonato, M., Del Curto, B., & Aurisicchio, M. (2018). Development and evaluation of a methodology to integrate technical and sensorial properties in materials selection.
Tian, H., Zhang, H., & Liu, T. (2019). Research on Material Selection of Product Design under Environmental Awareness.
Van Kesteren, I. (2010). A USER-CENTRED MATERIALS SELECTION APPROACH FOR PRODUCT DESIGNERS

Table 7. Material selection models throughout the years under the 2020 experience stages parameters

The table does not specify which material categories are considered for each model due to the simple reason that none of them have fully considered beyond Inactive ones.

In the broad aspects, the display of variables aims to show the evolution of material evaluations in design through the years, complementing the discussion of Chapter 1.

Furthermore, the table presents environmental needs as the mean explored by several authors to obtain product satisfaction. This is a variable dependant on external influences, part of cultural changes in growing global awareness.

The movement of environmental psychology, active since the 1960s, has been the precursor on opening the discussion for human-environment experiences, highlighting it as variables of strong impact in customer behavior, then, working as a competitive advantage when considered (Garling, 2014; Kopec, 2012)
Worldwide there is an increasing demand for ecological mind formation as an essential soft skill. Design practitioners are crucial for this change, being that they work as the nexus and skeleton for the product-making decisions (Akhmedova et al. 2020).

The issue here is that sustainability, even being such a relevant component to integrate into every project development, remains a non-mandatory parameter. In the bigger picture, knowledge of sustainable design should include insights for a Circular Economy but is seen by many designers as an additional (and sometimes inconvenient) criterion to the extent of factors to consider in the design path for which some are unwilling to incorporate it (Andrews and Robbins, 2010).

Fortunately, the pandemic has accelerated and positioned trends such as Wellbeing (Sustainability and healthy environments), Pragmatism (Self-sufficiency and Wealth in waste), and Kindness (Local love and Community) as the global targets for the designs of a post-pandemic future (Dent et al. 2020).

The vision of how and where to integrate the environmental parameter is still unclear. Some authors see the material selection model as an internal business focus that rarely considers external resource recognition, such as environmental needs.
Nonetheless, as stated in the previous Chapters, to support and guide the selection of luminescent materials under the digital era parameters, it is indispensable to consider external variables.

The selection method is the last layer proposed to evaluate in terms of literature review. This section aims to comprehend fundamental aspects and general structures for material selection to provide the base formation for the outcome platform.

3.1 Material selection system in the path of product design

Throughout the chapters, the correlation between user-context + material-product has been reviewed and stated in multiple layers. Even so, there is still a lack of decision-making methods that consider surrounding influences (both internal and external), e.g. sustainability, to help support the selection and integration of materials when developing a product (Prendeville et al. 2012). This aspect as we have observed is primordial especially for dynamic materials such as luminescent ones.

Material knowledge, as well as product design, feeds and grows within the iterations that occur in each period. Products reply to needs; needs reply to context. Products are made of materials, humans interact with materials, humans generate needs, and so on. With that thread of thought to conclude that the overall process of selection should work as a **holistic system influenced by the context** seems plausible (Ashby & Johnson, 2010).

Still, one of the most popular methods used product design for the selection of materials presentes a four-step strategy with problem-solving reasoning, and **internal business focus** (Ashby et al. 2010)**.**
The model starts by considering all the available materials, filtering options through steps of **identification** (context understanding), **selection** (adequate cluster), and **implications** (feasibility of selection). The strategy is proposed as follows:

> **Translation:** Express the design requirements of the project as function, constraints, objectives, and free variables.
> (E.g., optical glasses -Function: Enhance view; Constraints: Optically clear, Fracture toughness, Lightweight; Objectives: High volume rate, 5.000 units per week, minimize cost, medium durability of materials, recyclable; Free variables: Shape, cross-section area).
>
> **Screening:** The first cut, eliminate materials that don´t reply to the translation demands.
>
> **Ranking:** Organization of the materials that do reply to translation, from best to worst, a secondary cut.
>
> **Documentation:** Research family history of top-ranked candidates, third cut.

The process culminates with one or two materials selected adequately for the project. This strategy has been successfully implemented in **Granta Edupack** software, formerly known as CES, a toolkit for the evaluation of information for engineering design, used at over 1,000 universities and colleges worldwide[1].
This system has facilitated the design path and has been an astonishing contribution to a variety of disciplines involved in the product creation market. But, **in the design discipline, there is still some doubt about how and when to connect it properly with the path.**

On that note, Tung's (2012) argues the order of variables should be **first the local settings, products, and particular materials to work with. Then problems and opportunities are listed, providing a design based on the two previous. In that order, one would design based on where is located, with what is at hand, and not the other way around.**

Figure 48 takes this and other ideas mixing the content of the stages of design, the material profile plus the strategy for selection posed by Ashby et al. (2010).

1 Extracted from the web page of Granta Design. Available at www.grantadesign.com (Accessed: August 3, 2020)

The fusion exhibits the material selection system integrated into the overall design process a.k.a the path of design.

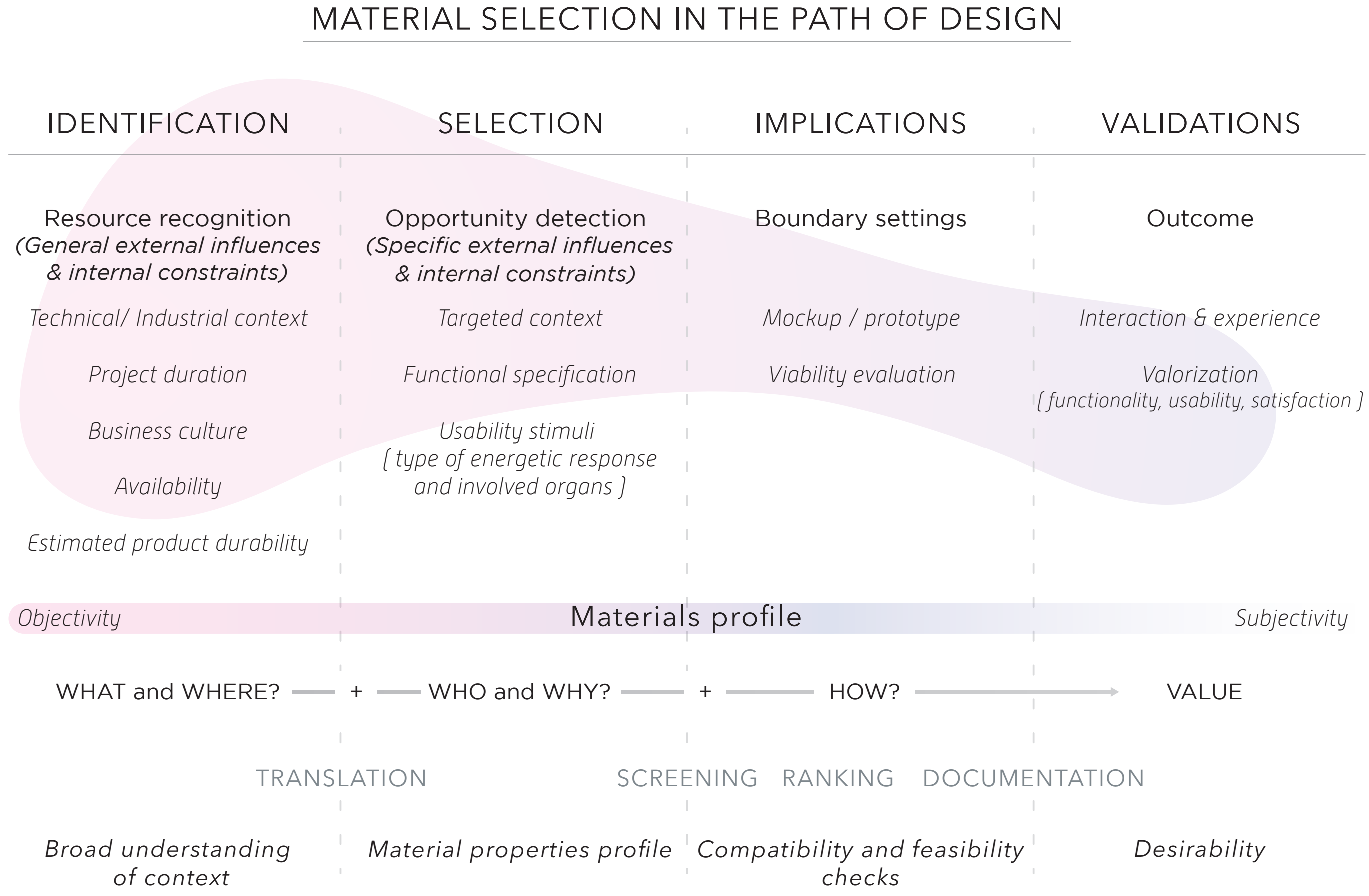

Figure 48. Fusing the material selection system in the design path, a proposal

Here we observe a proposal that questions the paradigm of the product as the main outcome and places **attention on the availability of resources, local contexts, necessary material properties for desire stimulus, then, the attention is placed in the experience**. This path simplifies how the variables interact and reciprocate each other, and aims to close the logical equation of 'what' +'how' leads to 'value' (Dorst, 2002).

This path is an extended elaboration to the one seen in Figure 2. Here, **the variables are presented under theoretical study** and elaborated considering the mentioned proposals together with personal insights.

Posteriorly the organization of how and when to carry the material selection process will be analyzed through targeted users' insights in Chapter 5.

3.1.1 Selection methods

In the material selection process there are several ways to convert 'raw' inputs, into a limited amount of logical outputs.
The ones proposed by Mike Ashby et al. (2010) **Analysis, Similarity, Inspiration, and Synthesis**, are presented and organized up next from the most structured and objective, to the freest and subjective.
The aim is to observe which of the following suits best the variables necessary to define luminescent materials under the parameters of the digital era.

Selection by Analysis:

Type of reasoning: Deductive - systematic
Type of knowledge required: Technical - 'fundamental'
Relies on: Quantification
Advantage of approach: Output justified in certainty
Disadvantage of approach: Rationalist structure might be too rigid for non-technical properties

Translation: Statement of requirements (Function: a climbing rope; Constraint: lightweight, L lenght; Objective: minimize cost)
Analysis: Performance metrics (equations to obtain the goal, e.g., analyze the relationship between strength and cost of material)
Identification: Recognize the materials that reply to the requirements
Screening: Select only those that maximize the performance metrics.

Selection by Similarity: (mainly used for substitution of materials)

Type of reasoning: Deductive
Type of knowledge required: Systematic - analogy based
Relies on: Quantification
Advantage of approach: Enables the integration of other material categories besides traditional
Disadvantage of approach:

Translation: Statement of requirements based on already known parameters (Function: a climbing rope; Constraint: lightweight, L length; Objective: minimize cost)
Edit: Work only with the indispensable constraints (the length variate by interacting with the elastic modulus parameters)
Identification: Recognize the materials that reply to the requirements
Screening: Selection of those that reply to the requirements

Selection by Inspiration:

Type of reasoning: Critical Thinking
Type of knowledge required: Connectivism
Relies on: Both quantification and qualification
Advantage of approach: Fosters creativity and innovation of products
Disadvantage of approach: It can implicate stubbornness in the subjectivity involved, individualization of actors

Translation mix: Statement of requirements (Function: optical glasses; Constraints: low durability, recyclability of materials; Interpretative: modern; Sensorial: light; Emotional: excited, relaxed)
Inspiration: Personal associations triggered by the requirements (supported by stimuli)
Screening: Selection of 'sense full' aspects to reply to the requirements
Ranking: Organization of feasible options.

Selection by Synthesis:

Type of reasoning: Inductive
Type of knowledge required: Analogy based - perception through experience
Relies on: Qualification
Advantage of approach: Promotes the growth of knowledge through cross-pollination between disciplines/ technology coupling.
Disadvantage of approach: Empirical output - based on probability

Translation by experience parameters: Statement of requirements (Interpretative: modern; Sensorial: opaque, light; Performative: pushed, turned. Emotional: excited, relaxed)
Synthesis: Combination of possible outcomes that reply to the requirements
Identification: Recognize the aspects that generate those specific stimuli (in already existent products or materials)
Screening: Selection of those that reply to the requirements

Currently all of these methods can be seen applied on books, digital software, online research, and so on. Facilitating and accelerating the selection methods since the early-mid eighties (as seen in Table 2). An approach to some digital tools and their coverage are discussed later ahead in section 3.3

Connecting the selection methods to what has been reviewed in Chapter 2, we observe Figure 49.

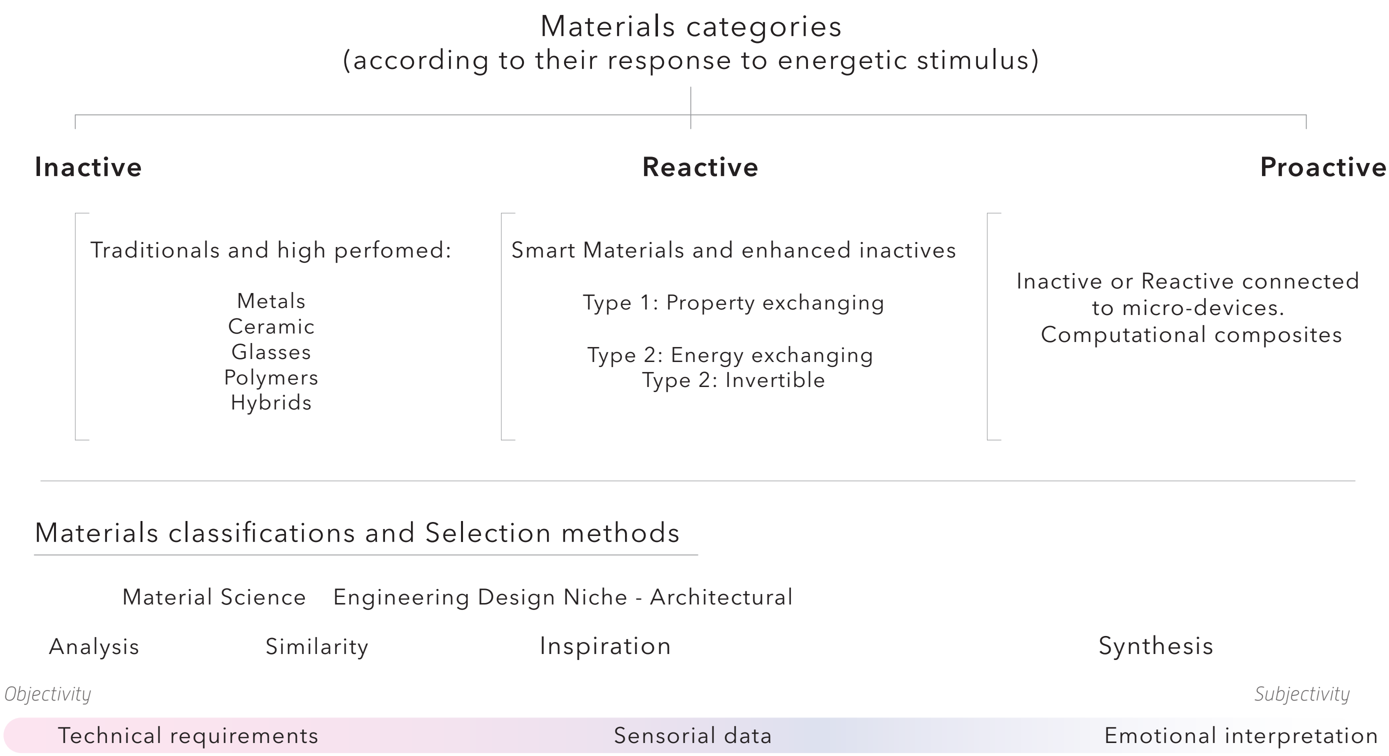

Figure 49. From material categories to selection methods

As said, the general inclination of selection processes is to work with inactive materials, science-led/analytic/technical requirements. Nonetheless, with the shift of perceiving materials as a source of also sensorial and emotional data, potentiated by the dynamism of reactive and proactive materials it is possible to conclude that methods such as **Inspiration and Synthesis enable easier incorporation of these categories as they open up to such variables.**

This integration can lead to accelerating material adoption (characterized by long gestation and acceptance periods, typically over 20 plus years) (Maine, Probert, & Ashby, 2005; Prendeville et al. 2012).

> *'What we need, especially when working with new forms of interactive materials, is to devise ways of* ***bringing the materials into the explorations earlier in the design process, and also make them a shared resource for everyone involved****, e.g. designers, developers, engineers, HCI-experts, dancers, psychologists, and end-users.'*
> *Fernaeus & Sundström, 2012*

For this to occur, there must be bridging of layers recognizing that context and subjectivity play a crucial role in each design project. The search is to enable the transformation of didactics into fluid exploration and developments, to maximize the material (education) selection in the design domain.

3.2 Material Driven Design

Traditional ways of educating designers around materials are proven to suffer from a lack of engagement. The learning process around materials should be about handling and **interacting,** rather than learn only through theories and tables (Zhou et al. 2018)

Proposals to help eradicate the rigidity of this educational structure and incorporate aspects such as the material experience have already been proposed, widely accepted, and slowly been integrated into the design discipline, such as *Meaning Driven Materials Selection* (Karana, 2009), *Expressive-Sensorial Atlas* (Rognoli, 2010), *Material Perception Tools* (van Kesteren, 2008), and *Material Aesthetic Database* (Zuo, 2010), as well as one of the most complete regarding selection parameters up to the date, MDD or ***Material Driven Design*** (Karana et al. 2015).

MDD is a fairly recent perspective that unfolds materials' possibilities by challenging designers to question **all materials as open, unfinished, or new and encouraging active exploration with them.** It corresponds to a method to highlight hidden problems, forgotten issues, open up new perspectives, ask new questions, define and present basic concepts of materials.

It centers the attention on **designing experiences, placing materials as the main point of departure in a design project.** It is an abductive process, generating new knowledge through experiments, connectivism, invention, and iteration, making products from what was previously invisible.

Material Driven Design suggests a blend of bottom-up (e.g. hands-on experimentation with materials) and top-down approaches (e.g. user studies, analysis of current trends), characterizing the material concerning both engineering performances and experiential qualities (Barati et al. 2019)

Several authors have claimed a preference for the material-centered method over representational ones (i.e. geometry-based CAD, visual collages, etc) due to its consideration between humans and nonhumans; instead of what has to be produced (Vallgårda, 2014; Coelho, 2007).

MDD organizes some activities, divided into four steps achieving a meaningful material application, here they are briefly presented according to the statements retrieved from Karana et al. (2015) and Barati et al. (2019):

> **Understanding the material**: Introductory step focused on awareness of both general functional and usability-sensorial needs. Direct manipulation/ material tinkering[2], benchmarking, user-interaction studies, and recognizing of 'materials experience 'patterns'.
>
> **Creating materials experience vision:** Centered on formulating the overall effect and intended experience. It considers both usability-intangible and satisfactory needs. The step ends with a summary of the findings, and potentials the material can offer; as a helpful guide for the posterior design decisions.
>
> **Manifesting material experience patterns:** Simultaneously 'materialize' and give 'meaning' to the product; bringing the relationships between appearance and action to focus (e.g. a doorknob affords to grasp and turning).

2 Tinkering fosters sensorial awareness of material qualities and encourages continuous development and perpetual prototyping. Material Tinkering aims to extract data, understand material properties, understand constraints, and recognize its potentialities by exploratory research of trial and error, sensing, documenting, associating. (Louridas, 1999; Jung, & Stolterman, 2012).

Creating material/product concepts: The final step aims to update and/or modify both the samples and feasibility aspects of the material according to the specific requirements of the project.

The shift in designers' attention to what materials offer in direct experimentation, allows MDD practices to approach 'making' as a way to unfold the material's capabilities in very-fine-grained fashion. The sensitivity for the qualities and actions elicited by the material in interaction equips the designer with a broad understanding. (Giaccardi et al. 2015)

This complex model takes advantage of the available knowledge and resources in the surroundings. It is a well-articulated option for how to proceed when a **'material' is a tangible starting point in the design process and 'experience' is the outcome,** which virtually accommodates the considerations we have encountered for luminescent materials.

Understanding that the COVID-19 outbreak has accelerated our dependence on the intangible-immaterial aspects and that every transaction, including designing and its related processes, is shifting into a 'distant mode' **how could we provide a tangible experience, as of MDD, into a digital one?**

MDD is the last model reviewed in this thesis, in a section focused on analyzing methodologies for material selection in the design field, searching to find the best recipe to incorporate and exploit luminescent materials.

The next section focuses on analyzing the market state on the selection of dynamic materials in online platforms, approaching references to guide our outcome.

3.3 Digital tools for material selection

Our current reality involves digital interconnections and communication through screens. The role of the digital artifacts and the Human-Computer Interaction (HCI) -as the intersection between the physical and the digital world- has opened access and dialogue, and now is the rule in this pandemic reality.
With the exponential demand of online platforms to support information, enabling development at distance, the issue has become to find the balance point and criteria to select and organize proper information.

Years ago, Manzini and Cau (1989) already defined objects as situated at an intersection of development of thought (models, cultural structures, forms of knowledge) with technological development (availability of materials, transformation techniques, forecasting, and control systems).

The path of these technological developments that considers Ubiquitous Computing (Ubicomp) (Weiser, 1991), and the Internet of Things (IoT) (Ashton, 2009) comes together with the idea of dematerialization (Campenhout et al. 2013) of content and information, digital world interactions, that bridge the material and immaterial layers.

Under the vision of tangible bits (Ishii and Ullmer, 1997) and an approach of experimentation as of MDD, designers started to produce **Tangible User Interfaces** (TUI), a bridge between smart materials and technologies that enable the manipulation of digital data through the physical environment, being the evolution of **Graphical User Interface** (GUI), that offers a standard display of information in electronic devices.

The next step envisions a future of human-material interactions (i.e. the equivalent to Proactive materials), where the material responds as a direct interface, becoming **Material User Interface** (MUI), based on the implementation of **Radical Atoms,** defined by Ishii et al. (2012) as,
'future materials that can transform their shape, conform to constraints, and inform the users of their affordances'

Figure 50 presents a series of User Interfaces, organized from left to right in respect to the level of interaction depth with the user.

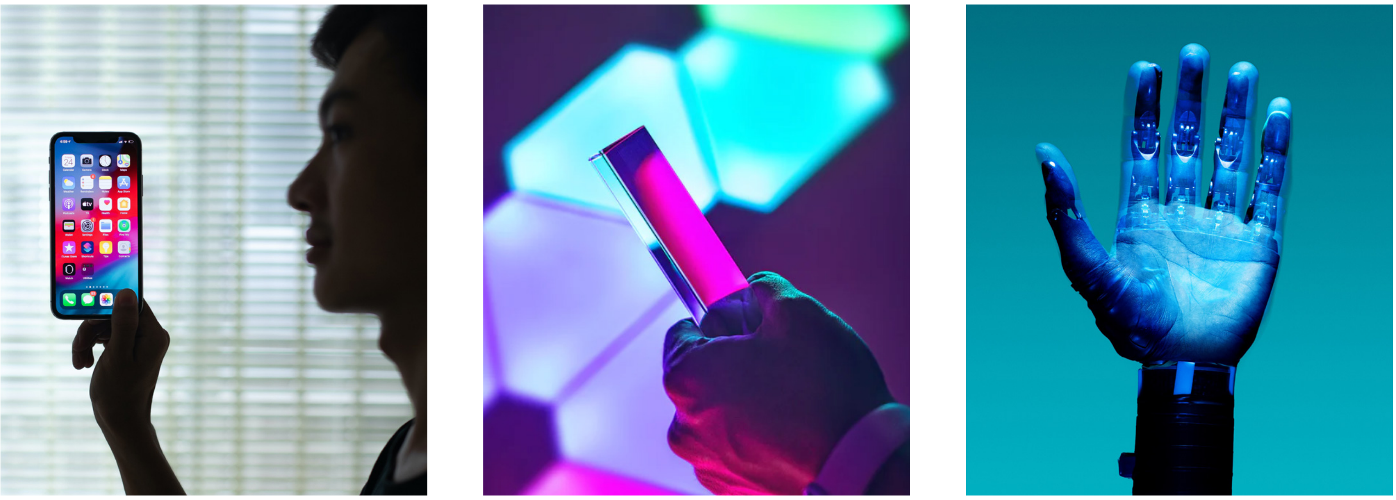

Figure 50. User interfaces, interaction depth

The symbiotic relationship between materials and technology, bridge by user interaction is the medium that fosters Reactive and Proactive materials' dynamic functions and responsive behaviors.

The unlimited design potential and infinity of experiences these materials can allow challenges designers and researchers to handle complex compositions of physical and digital qualities.
For which is important that, same as when carried for inactive materials, for the designer to be able to distinguish the characteristics of each kind and their potentialities. To our interest, recognize the characteristics and potentialities of luminescent materials.

As stated by Fernaeus and Sundström (2012), there is a need to develop 'methods for material exploration,' and means to communicate these 'material properties and possibilities'.

A phenomenon consequence of the available technical resources for digital exploration and crafting (i.e. investigation and selection platforms, computer-aided design tools, web-based prototyping, and production processes) have also impacted an increase of community engagement. Online communities are blurring the roles of suppliers, designers, users, and manufacturers day by day. This process can bring new cultural values and business models with an unprecedented concept of the digital ecosystem (Jung & Stolterman, 2012; Bonanni et al. 2008), this factor is even more important to consider in our remote reality.

In the last twenty years, several databases (i.e. a tool with information regarding one or several 'materials families' and their properties, and may be reported to the different material manufacturer) and software initiatives (i.e. an application that manages the information of one or several databases, and the kind of information depends on the utilized database) have been created to allow designers and engineers to consult for materials properties and characteristic (Ramalhete et al. 2010).

In 2010, Ramalhete et al. carried a study of 87 available tools for material selection, both online databases, and software, in the design discipline according to:

- The extent character of the tool (very specific databases or software were not considered, for instance: material selection for dental prosthesis).

- Possibility of selecting materials (the cases that only allowed selection of manufacturing processes were excluded).

- The number of materials (did not include databases with a number inferior to 12 materials).

- The usefulness of the design activity

The analysis of such platforms provides visualization on how these tools are generally structured and build-up, besides referencing which parameters are indicated and how they are attributed.

For our purpose, the study allows approaching how dynamic materials are being integrated and presented to the user, responding as an indirect user study.

From the extended list of 87 tools, a filter was carried, retrieving only online databases that are relevant in the market, with actualized information (databases dedicated only to one family, class, or subclass of materials, were not considered), providing an outcome of 7 online platforms for further evaluation.

Supported by the work carried by Hölter (2019); a benchmark was carried to discern the offers of these platforms regarding variables that respond to trends of the digital era, discussed along the length of this thesis:

- Using mode (Business model)
- Resources availability (By location, by suppliers)
- Material categories inclusion (Inactive, Reactive, Proactive)
- Material classifications (Material Science, Engineering, Design niche - Architectural)
- Selection properties (Functionality, Usability, Satisfaction)
- Community collaboration (Consultations and validations)

The evaluation of the Business model focuses on accessibility to information discussed in section 1.2.1, meaning OER, the democratization of knowledge, and the possibility to analyze and investigate materials without paying.

Resource availability corresponds to the recognition of local and global surroundings, can I find suppliers that are nearby my location? Can I recognize materials according to my perimeter characteristics? This particular variable also provides information that can be useful to define more clearly intangible variables and trends per localization.

This first study aims to filter which of these tools are useful to further evaluate for our purpose, as well as providing the first idea of a possible combination of elements for a posterior structure.

Table 8 present the information following the organization of the *'type of digital tool'* defined by Ramalhete et al. (2010). At left, **informational tools** (provides technical information on materials, and present information in textual descriptions). At right, the **inspirational** type (they provide information about different materials and show visual data to stimulate brainstorm).

It is important to mention that platforms that fully incorporate dynamic materials, or are designed to propel their characteristics could not be found.

		Database name	matweb	total materia	materials project	matmatch	material connexion	material district	damadei
USING MODE	Free	Free	○	○	○	○		○	○
		Demo software		○					
	Paid	Annual		○			○		
		By access	○						
		Another				○			
RESOURCE AVAILAB.	Yes	By location							◉ *ONLY IN EUROPE*
		By database of suppliers				○	○		
	No		○	○	○			○	
MATERIAL CAT.		Inactive	○	○	○	○	○	○	○
		Reactive			○		○	○	●
		Proactive							●
MATERIAL CLASS.		Material Science			○				
		Engineering	○	○		○	○	●	○
		Design Niche - Arch.						◉	
SELECTION PROPERTIES	Satisfaction	Environmental		○ *ONLY ULTRA PACKAGES*			◉	○	○
	Usability	Intangible							
		Sensorial				○	○	○	○
	Functionality	Manufacturing		○		○	○		○
		Economical							
		Technical	○	○	○	○	○	○	○
COMMUNITY COLLAB.	Consultancy	Free			◉				
		Paid	○			○	○		○
	Validations	Free			◉				
		Paid							

LEGEND ○ *= Present* ● *= Stands out* ◉ *= Market advantage*

Table 8. Benchmark of a selection of online databases

From our list of variables, two are indispensable for our evaluation of platforms by the evidence provided in previous chapters,

- **Free access for research and investigation (OER)**

- **Coverage of material categories (more than just Inactive)**

Under these parameters, only three platforms respond to the needs, Materials project, Material district, and Damadei.
Two of the three options presenting inspirational or synthesis methods were provided for the search, corresponding with the conclusion of section 3.1.1.

From the comparison it was also possible to observe market gaps providing opportunities to exploit:

- **Availability of resources according to location**

- **Hybrid between both informational and inspirational databases**

- **Accessibility to environmental properties**

- **Community assessment and collaboration**

Moreover, we can conclude there is an evident **lack of considerations for Intangible properties.** None of the studied platforms registered any guidance regarding the topic.
As established previously context considerations provide a more direct connection with users, leading to associations of experiential qualities of materials into defined groups. This could help to define experience patterns.
This topic remains of relevance and will be discussed again further ahead.

Previous carrying the markets study portion of this thesis, the research question, methodology, and objectives will be established in Chapter 4.

Chapter summary

Material selection models are shifting to consider parameters that reply to Functionality, Usability, and Satisfaction, related to the product experience and translated as the product value.

User-centered, material-centered methodologies and sensorial properties have been incorporated during the last decades into material selection models expanding the variables and replying to a functional-hedonic system. Even so, the approaches prevail in science-led/analytic/technical rigidity, that reply mainly to Inactive materials.

To provide access to material categories such as Reactive ones, enabling materials like luminescent ones to be explored there must be a transformation of didactics into fluid exploration to maximize the material (education) selection in the product design discipline. This approach can be carried following methods such as Inspirational or Synthesis.

A selection method able to reply to the parameters of the digital era, adapted to dynamic materials should recognize both internal and external variables, taking advantage of one or more of the detected market's gap:

- Free access for research and investigation

- Availability of resources according to location

- Hybrid between both informational and inspirational databases

- Accessibility to environmental properties

- Community assessment and collaboration

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Chapter 4:

Approach and methodology

4. Approach and methodology

This thesis has explored and stated the parameters that rule product design and material studies under interaction means. The evolution of models has been reviewed up to arriving at current waves that define materials as sources of functional-hedonic information, formulated by technical, sensorial, and intangible aspects.
These changes respond to the advances achieved in the digital, accelerated by tools of open source, having repercussions both in material development and material education of the field.

As a consequence of the previous, new categories have been defined. The arrival of dynamic materials able to change color, shape, emit sound, among other effects, have produced more engaging, complex user experiences, blurring the limits between the physical and the digital.
In that group, we can find light-emitting luminescent materials, efficient, versatile, environmentally friendly, able to affect our perception of products and surroundings.

Being present in our everyday products (screens, windows, luminaires, medical devices, etc.) and in exponential growth, the understanding and incorporation of these materials seem fundamental for product designers' systematic choices.
With this notion, there is an increasing interest to provide new decision-making methods into the field, as tools that could disseminate the material into properties that appeal to its technical, sensorial, and intangible aspects, providing the possibility to designers to investigate them by formulating experiences.

The preliminary research, connects these three layers, setting the ground base for the goal of this thesis, to propose a platform framework designed to support and guide the selection of luminescent materials under the parameters of the digital era (i.e. open educational resource and experience focused).
Due to the several aspects to consider for this outcome, the presented study focuses on building a prototype for visualization of the tool as further studies would be required to provide a functional model.

The outcome aims to serve designers students and early practitioners as a material inspirational, decision-making method, guiding and promoting creations through the product design path.
The use of such kind of tool expects an outbreak of luminescent product innovations, together with constant content upgrades provided by OER platforms' user feedback. Moreover, it could foster uses of luminescent materials in new industries, generating unexpected impacts.

Critical thoughts

- Luminescent materials potentialities are best achieved once their properties have been established and recognized. Design with the material as the input and the experience as the outcome (as proposed by MDD).

- To potentiate the incorporation of any kind of dynamic materials in the field there must be an analysis of the current needs and offerings. Their acceptance depends on the right balance between what is known and what needs to be taught.

- Suggested as an OER tool, the platform needs to evaluate different product design field users, students and practitioners must be consulted.

Before stating the questions, let's be reminded of a quote that has had strong impact in this research:

*'What we need, especially when working with new forms of interactive materials, is to devise ways of **bringing the materials into the explorations earlier in the design process, and also make them a shared resource for everyone involved**, e.g., designers, developers, engineers, HCI-experts, dancers, psychologists, and end-users.'*
Fernaeus & Sundström, 2012

Research Questions

How do actors involved in the product design field carry the selection process? At what stage of the design path do they carry it? Is there a congruency across nations? Are they acquainted with ICS materials?

What elements (categories, properties, structures, paths) can we reference from existing databases that already incorporate materials such as luminescent ones that could help us elaborate the platform framework?

Responding to both market's offerings and needs regarding dynamic materials, what information is indispensable to present, and how should it be structured?

Methodology

To provide an answer to the previous questions, this research is structured as design-led and responds to the Double Diamond Model (Council, 2014), consisting of a total of four phases.

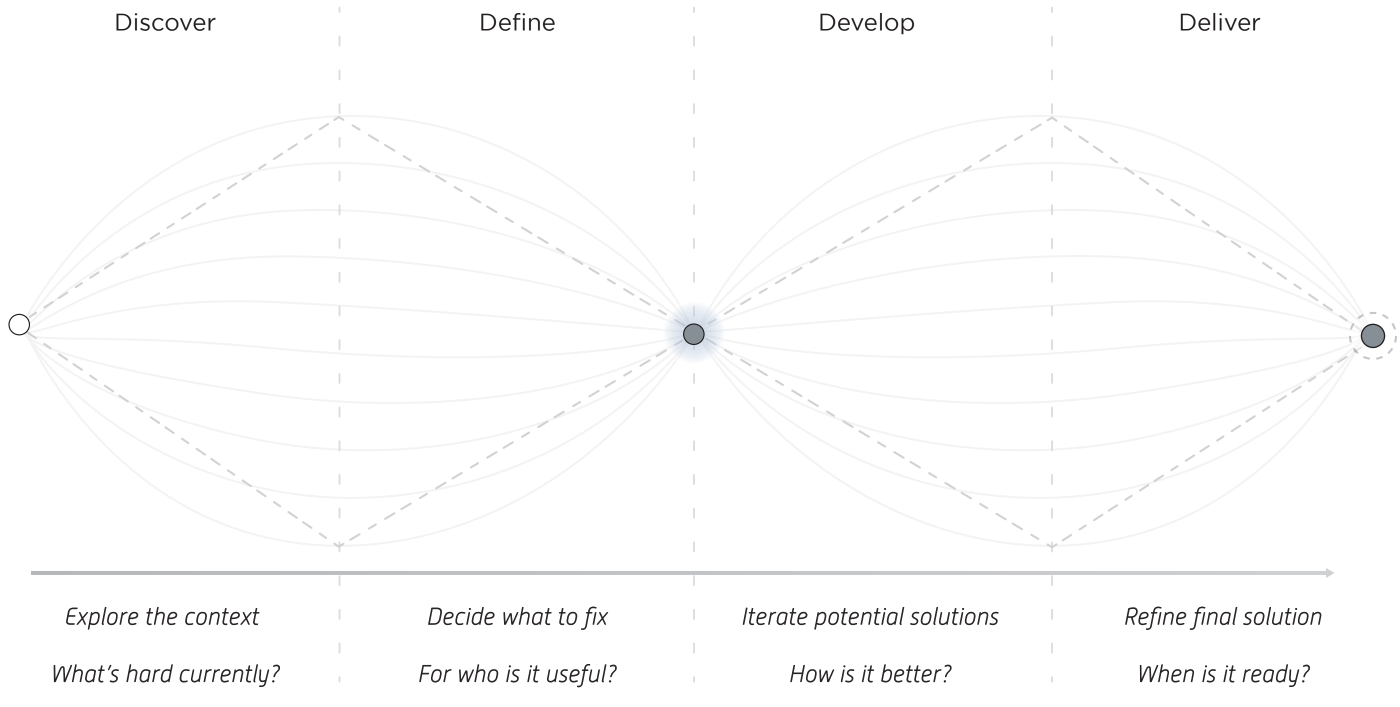


Figure 51. Double diamond model

Each phase comprehends:

Discover: Investigation conducted through literature review, analysis of 16 case studies of luminescent materials, and benchmark of available databases that fit the criteria. The phase is comprehended from Chapters 1 to 3 and establishes the parameters that intersect product design, materials, their selection, and technology, reflected in luminescent materials.
This phase is essential, as it provides insights regarding luminescent materials, their working principle, types, forms, and potentialities, and how to evaluate them in the field.

Define: Aiming to provide light to the questions, a comparison of the market's needs and offerings is provided by carrying a questionnaire to obtain insight of possible users (product design students and early practitioners) regarding their knowledge of dynamic materials and their process for material selection.
The information is taken into consideration to generate a database analysis of established platforms in the field (selected from the benchmark presented in Chapter 3).

In this stage, a correlation between the theoretical knowledge discussed in the Discover chapters is obtained by contrasting structural setups, categorizations, and indexes observed in functioning platforms.

The section finalizes with observations of content, providing definitions of properties selected to be incorporated in the platform. This has been retrieved either from the literature review, case studies, or a questionnaire provided for targeted users designed for the recognition of intangible properties.

Develop: Definition of structure, organization, navigation mode and properties the platform provides for the support and incorporation of luminescent materials in response to the offers and needs detected in the product design field.

Deliver: Presentation of the platform accompanied by a resume of the project contributions and a critical analysis of aspects for the future growth of the project.

This thesis was carried in its totality in the cities of Viña del Mar & Santiago de Chile, during the COVID-19 pandemic, under the context of social outbreaks for constitutional changes in the country. For safety reasons, all user-collaborative activities are executed remotely, in online modalities.

Chapter 5:

Opportunity detection

5. Opportunity detection

Understanding that the topic of luminescent materials and their evaluation is rather specific, a questionnaire was provided to design students and practitioners of the field to identify in the macro level the level of knowledge, organization, and approach they managed regarding material categories and their selection. This resource aims to provide insight regarding the needs of users, providing insight for possible structures and organization systems the platform could provide. The analysis in this section is developed to respond to the research questions.

To review the questionnaire, please see the Annex.

Provided both in English and Spanish, the questionnaire was delivered to students and professionals involved in the areas of product design and fabrication from the Southamerican (SOUTHAM) and European (EU) markets.
Here the search is to highlight general cultural similarities and distinctions regarding the knowledge of material categories, recurring properties considered, and overall approach to the material selection process to envision what parameters are necessary to reinforce or eliminate in a platform designed for the selection of a specific dynamic material.

The scope provided a total of 30 answers, with participants native from Chile, Argentina, Brazil, Ecuador, France, Italy, Germany, Denmark, Macedonia, and India, currently based and scattered over the continents of South America (10 repliers) and Europe (20 repliers).
The participants, 19 males, 10 females, and 1 other presented an age range between 23 and 44 years, with an average age of 27 years old. Fourteen of them are students at the master level, mainly EU-based, while sixteen are workers with a range of 4 +- 2 years in the product design industry.

The general information of the participants can be seen in Table 9.

Country of origin		Chile	Argentina	Brazil	Ecuador	France	Germany	Italy	Denmark	Macedonia	India	TOTAL
Repliers		9	2	1	1	1	1	9	1	1	4	30
Gender	F	5	-	1	1	1	-	1	-	1	-	10
	M	3	2	-	-	-	1	8	1	-	4	19
	O	1	-	-	-	-	-	-	-	-	-	1
Occupation	S	1	-	-	-	1	1	8	-	1	2	14
	W	8	2	1	1	-	-	1	1	-	2	16
Current market		SOUTHAM	EU	EU	SOUTHAM	EU	EU	EU	EU	EU	EU	

LEGEND | F = *Female* M = *Male* O = *Other* S = *Student* W = *Worker*

Table 9. Questionnaire participants general information

The highlights of the answers are as follows:

- From the total sample, 40% of repliers carry out the material selection in the concept creation stage, 57% during the embodiment, and only 3% at the detailed design.

- Only 40% of the participants declare to be acquainted with Reactive and Proactive materials. Currently, they are all based in Europe.*[1]

- 97% of participants declare an interest to know more about Proactive, Reactive, and Inactive materials, in that order. (this particular analysis aimed to validate there is market to introduce dynamic materials)

- The dominant justification why participants don't access a wider spectrum of materials are lack of time and unawareness of where to obtain the information.

Regarding the selected properties and their prioritization, a set of six types were presented, as seen in Table 3. Technical, Manufacturing, Economical, Sensorial, Intangible, and Environmental, with considerations of each. Then asked to organize from most important in the selection process (1) to least (6). Posteriorly asked to rank from most managed (1) to least (6). The replies by the market are as follows:

- **European-based participants follow a traditional approach. Placing functional properties such as Technical and Manufacturing as the most utilized, while Ecological takes a back seat, overlooked by 30% of the repliers, and 55% claimed to dismissed Intangible properties.**

- On the other hand, South-American based participants seem to have a more scattered relevance for properties. They highlight the importance of Technical, Ecological, and Economic properties, while 20% dismissed to consider Manufacturing requirements, and 40% mentioned not to integrate Sensorial properties.

To comprehend the source to obtain material information, a list of also six options was provided, considering Books, Suppliers catalogs, Fairs/seminars, Softwares (Granta Edupack or other), Online platforms (Materialdistrict, Matmatch, Materiom, MaterialConnexion, or other), External consultancy, asking to list from preferred (1) to least used (6)

- EU-based actors source of information is obtained through External consultancies, Software, specifically the Granta Edupack software[2], and Books.

- SOUTHAM-based actors preferred information sources are Free access platforms and Seminars.

The analysis carried in the next pages together with Figures 52 and 53 shows each market's paths, categories coverage, and properties prioritization, enabling us to compare and to start elaborating on possible adaptations for our proposal.

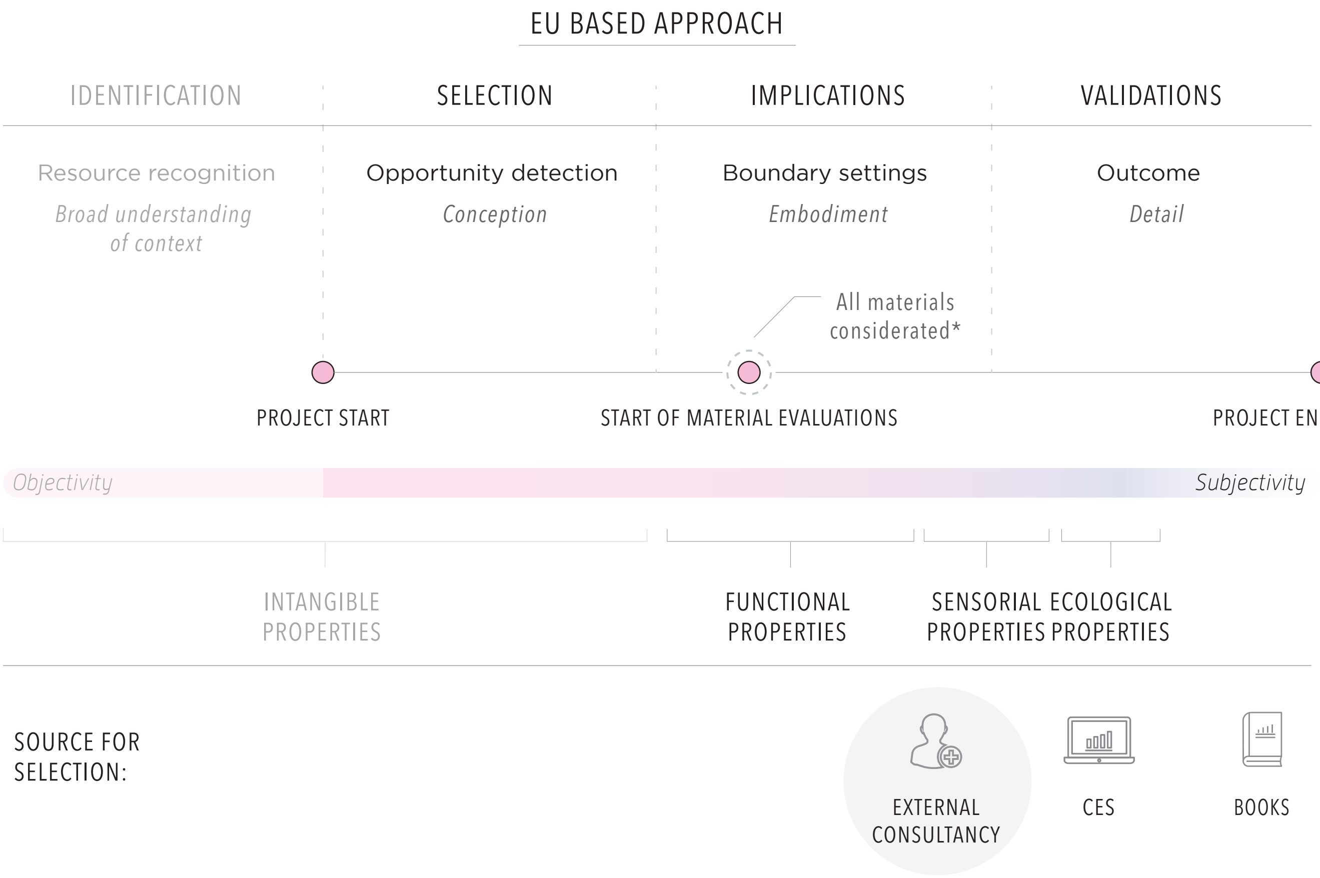


Figure 52. EU approach to material selection in the design path

Analyzing individual replies, in the case of the 20 EU-based actors, it seems there is a growing tendency to incorporate materials from an earlier stage, comprehending their relevance since the product conception.
Moreover, there is an interest to manage and learn more about material categories and properties, but **stated unawareness of where to obtain such information**.

Moreover, EU-based participants express Functional properties as more relevant than others, ensuring them as the objective to accomplish.
Following that same train of thought, **there seems to be a predilection for technical, informational data**, and selection methods such as Analysis and Similarity. The most used sources for selection are external consultancies, CES, and books.

Still, **45% of repliers stated no to be satisfied with the available resources for material selection with they were acquainted.**

Moreover, a list of 11 topics was elaborated considering offers detected from the platforms reviewed in section 3.3 (see page 106) to be ranked by the participants according to their desire to access in a platform when selecting materials, from most relevant (1) to least (11). The four most relevant were selected as follows, in the provided order:

- **Material categories (Inactive, Reactive, Proactive)**
- **Processes**
- **Trends (Most popular searches in the platform) (*)**
- Researches (Articles, tests, and tryouts of/ on materials)(*)

The **topics provided in bold** correspond to those selected with a **high relevance** (above or equal to 5) **in both markets**. To see the full list of 11 topics, please check the annex.

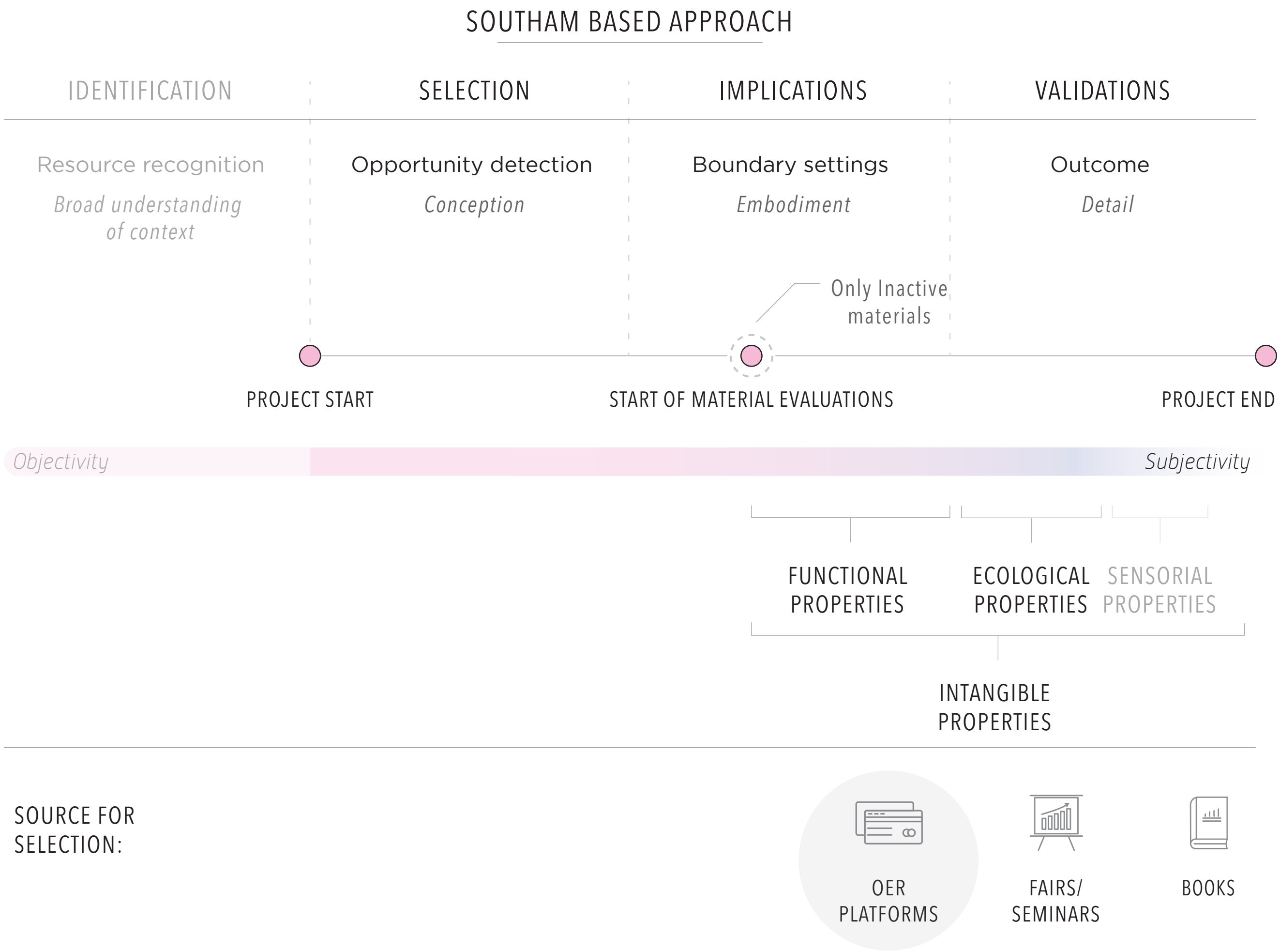


Figure 53. SOUTHAM approach to material selection in the design path

For the 10 SOUTHAM-based actors, there is **less congruency regarding when and how to approach each property.** Technical and Economical aspects guide the selection, but the culture in this continent views nature as a source of value for wellbeing. For this reason, Intangible properties are managed intrinsically throughout the path, while Ecological properties take a close third spot with a projection to shift to an early stage

In this case, there were also comments regarding the intention to incorporate materials from an earlier stage, understanding benefits if the evaluation was done since the product conception.

Repliers stated to be acquainted only with Inactive materials, guided by sources where they declare 'information will be detailed and easy to find.' Preferring free access platforms and seminars.
SOUTHAM actors **seem to prevail in their searches with an Inspirational and Synthesis approach.**

Even so, **50% of repliers stated no to be satisfied with the available resources for material selection with they were acquainted.**

For SOUTHAM-based participants, the four most relevant topics listed to access were:

- **Material categories (Inactive, Reactive, Proactive)**
- Finished products (*)
- **Processes**
- **Suppliers (With availability by location)**

It is possible to observe there isn't global congruency for material selection, and there are variations regarding the selection approach under socio-cultural context, lacking a shared approach. Moreover, **property prioritization varies not only by market but also by the project, implying the relevance of liberty in the selection of each property**.
Furthermore, not all professionals nor students are familiarized with ICS materials, stressing the need to teach and incorporate such materials.
Moreover, it would seem that the theoretical functional-hedonic parameters studied for evaluation of materials in the field are not clear or even known for most users, for which the platform would have to introduce such topics and explain their relevance.

Both scenarios expressed **difficulty to spread and depth the levels of research regarding materials**, due to a mixture of **lack of time and complexity of variables to manage (i.e. a paint point for when approaching the selection process).** Unaware of where or how to retrieve information, this would seem to be translated as discontent or lack of management regarding the topics.

Clarification of the impact of properties in the experience outcome could help enable communication and ease product creation between actors, facilitating acceptance of new materials.

This conclusion stimulates the notion that decision-making methods able to guide on possible solutions accommodate more to the wide variety of approaches designers could have, incubating curiosity on how to approach a possible experience more than providing a direct answer to a problem.

Regarding content, there is clarity on the most requested topics to address for both markets are:

- **Material categories (Inactive, Reactive, Proactive)**
- **Processes**
- **Trends (Most popular searches in the platform) (*)**
- **Suppliers (With availability by location)**

Moreover, there seems to be an interest to carry the process considering the work of pairs for inspiration/references, as seen in the topics marked with an (*), these correlates to the theoretical information provided by literature review and the search for OER tools characteristics of the era.

5.1 Database Analysis

From the previous information, it is possible to conclude that **the number of variables to manage combined with a lack of clarity of when to approach them, plus time limitations would seem to be one of the hampers in the selection process and inclusions for new materials.**

Understanding that platforms that fully incorporate and distinguish dynamic materials, or are designed to propel their characteristics could not be found. This analysis aims to answer our second group of questions 'What elements (categories, properties, structures, paths) can we reference from existing databases that already incorporate materials such as luminescent ones that could help us elaborate the platform framework?'

A scope of 3 main platforms was selected from the list presented on page 109, Table 8.
The selection requirements were established according to the line of study of the thesis and based on the highlights carried on page 110, together with the remarks of the previous section, defining that:

The evaluated platforms must reply as free in their mode of use, enabling OER research and investigation, and they **must incorporate a database that presents dynamic materials**.

Three platforms meet the criteria, **Materials project, Material District, and Damadei**. Nonetheless, a fourth platform will be considered, due to the convenience of its organizational structure, as it would seem to be an important aspect to reply to the markets' needs, the platform is **Matmatch**.

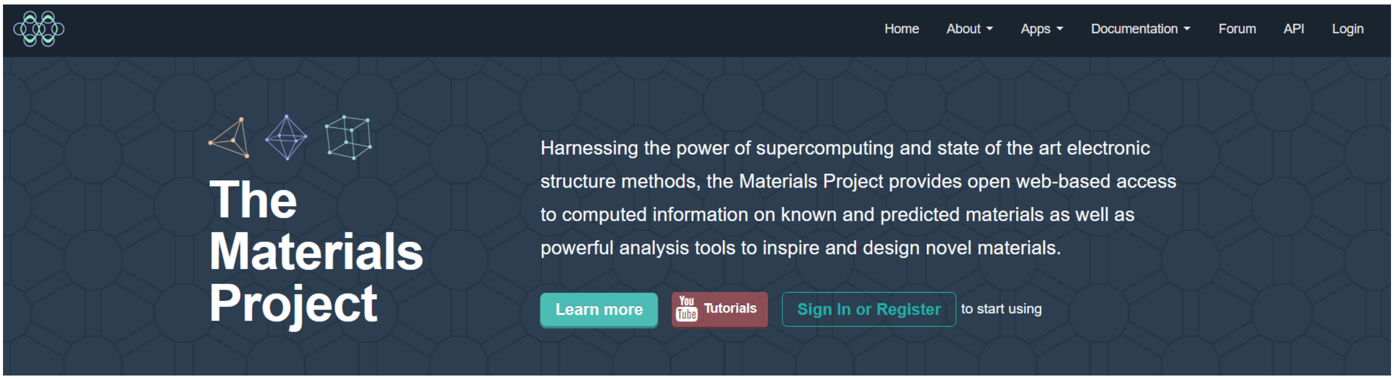
This stage aims to expose two main aspects for our further development:

- to understand how tools for material selection and material exploration are build and structured;

- to observe methods in which ICS materials have been integrated and presented to the user

The databases are presented from Informational (provides technical information on materials, and present information in textual descriptions) to Inspirational (they provide information about different materials and shows visual data to stimulate brainstorm).
Leaving Matmatch to be analyzed at last.

Materials project:



materials
project

www.materialsproject.org

USING MODE	MATERIAL CAT.	MATERIAL CLASS.	COMMUNITY COLLAB.	SUPPLIERS AVAILABILITY	SELECTION PROPERTIES
Free	Inactive Reactive	Informational Material Science	Free consultancy Free validations	No	Technical

Figure 54. Materials project presentation

'Materials Project (MP) is a community resource for theory-based data, web-based materials analysis tools, and software for performing and analyzing calculations ***to accelerate materials design and education by providing new data and software tools to the research community.*** *MP develops or contributes to several open-source software libraries, developing tools to help researchers share their data (both computational and experimental) through its platform'*
Jain et al. 2018

MP rests on a database of predicted properties of materials, the result of executing millions of density functional theory (DFT) simulations on supercomputing resources. It combines and visually presents the data for specific analyses such as phase diagram generation or battery electrode evaluation.

The platform aims to question the materials design paradigm by enabling scientific and industrials studies through a **compositional driver, and selection by analysis** as presented in Figure 54.

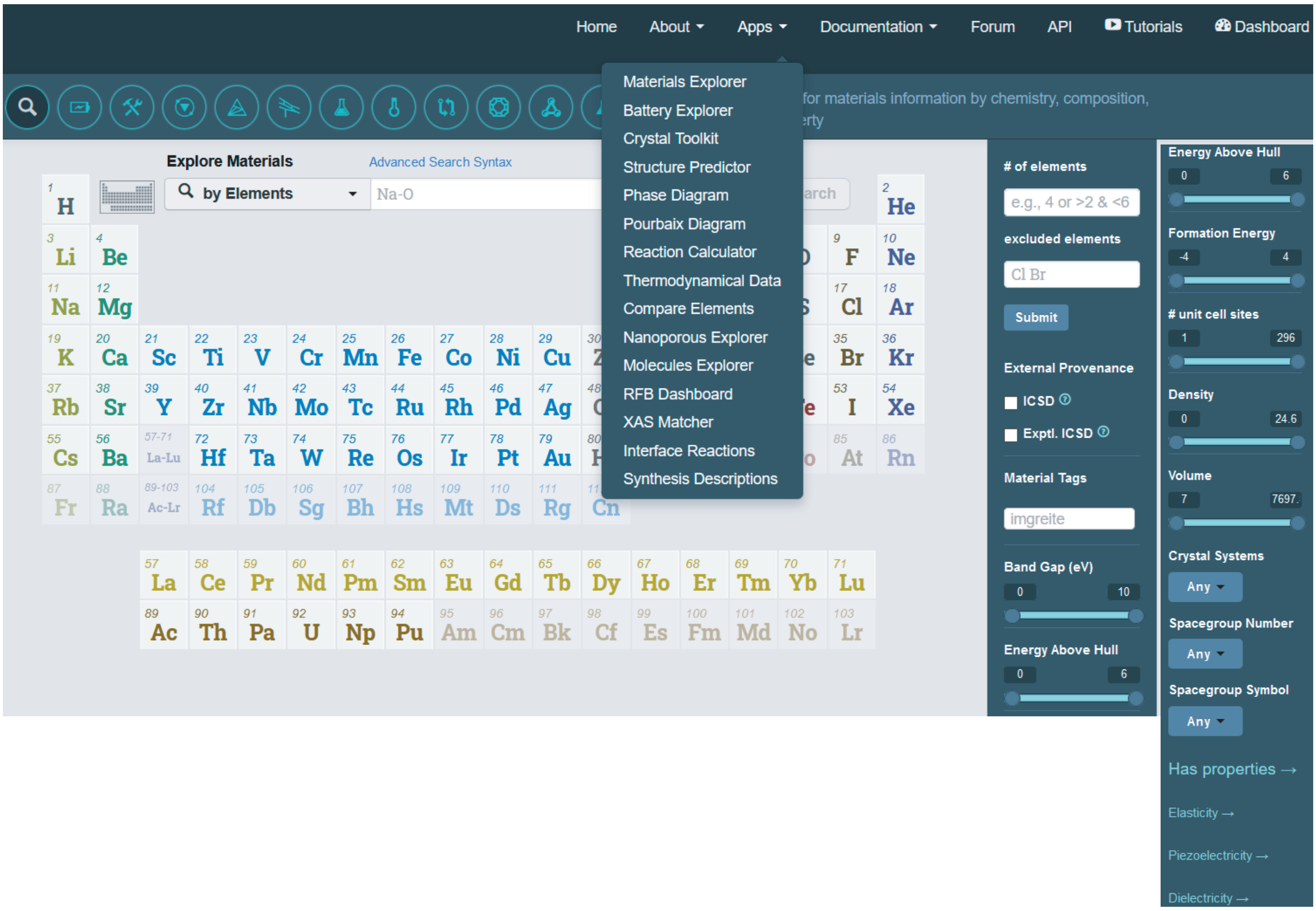


Figure 55. MP screen of parameters for materials evaluation

As can be observed in the image, the platform works at the micro-level. Parameters for the organization considering categories, properties, or processes are not present, nor there is guidance for the latest projects or trends evaluated in the platform.

The platform does focuses on promoting collaborative work through Materials Application Programming Interface (API) and the open-source Python Materials Genomics (pymatgen) and provides spaces for evaluation and collaboration of analysis through an open Forum, as seen in Figure 56. While Figure 57 contains an example of the interaction with the material structure.

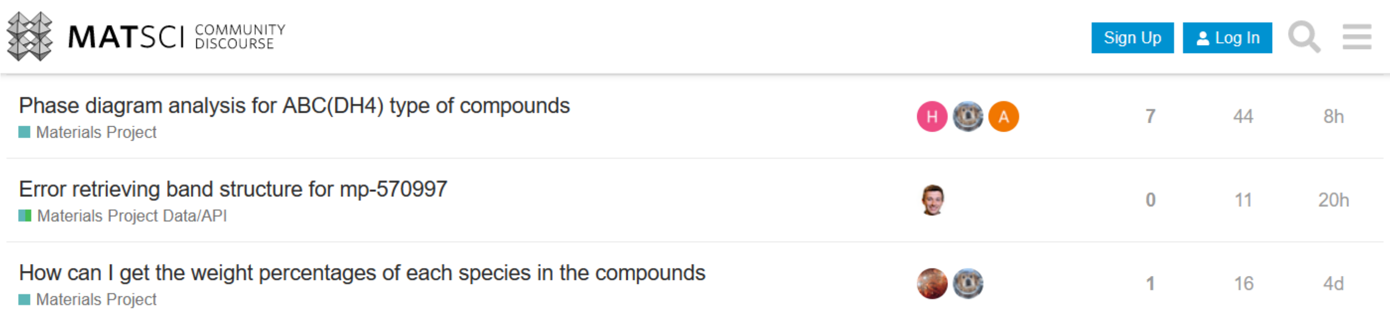


Figure 56. MP screen of collaborative forum

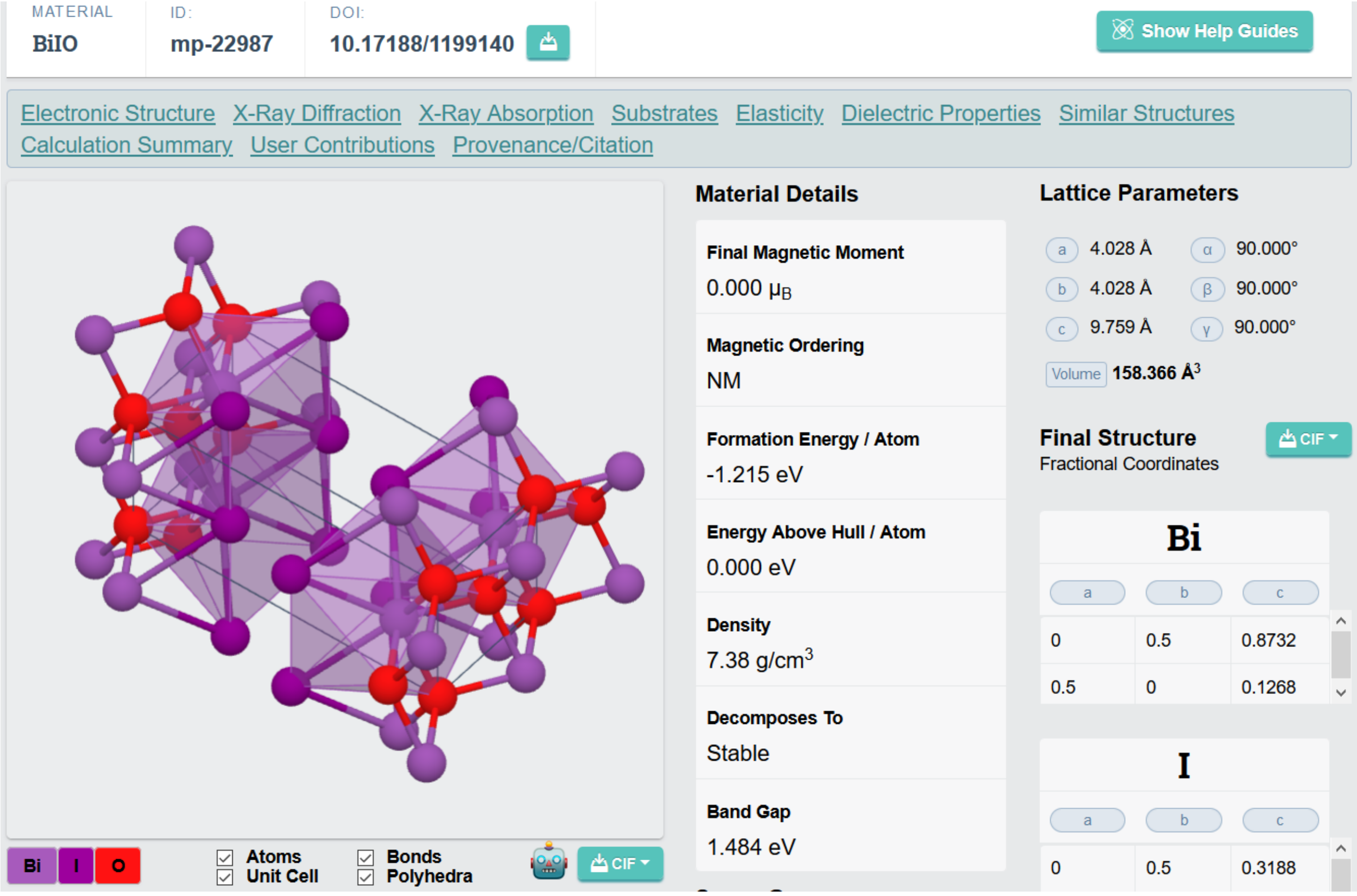


Figure 57. MP screen of interaction with material structure

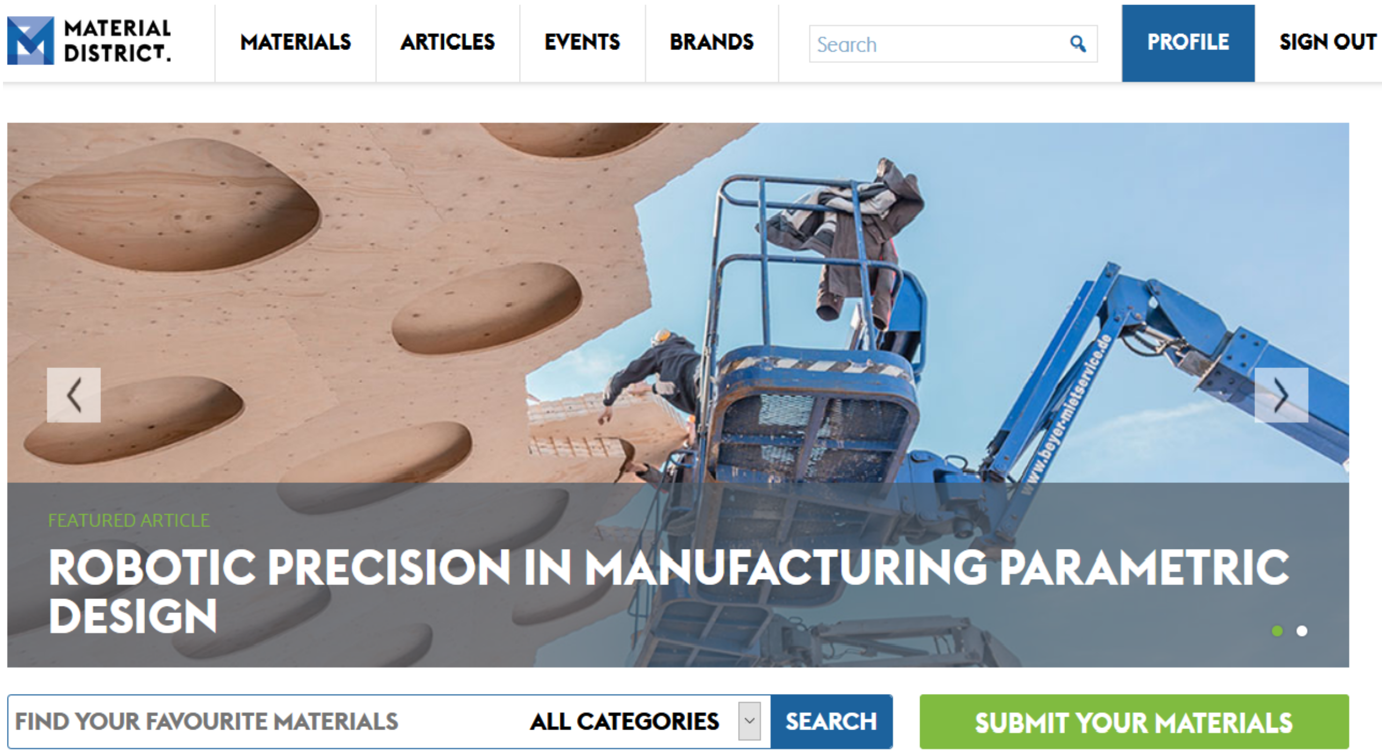
MP materials database is related to the number of investigative users. There is no registration of the number of materials the database support, nor defined families or categories, as mentioned previously. Here the platform supports explicitly curious, investigative approach, providing the tools for the user to play and invent. Due to the same consideration, the main difficulty is that the user must know about Chemistry and Programming or be able to investigate on its own to produce contributions.

By 2018, after seven years of being active, the platform stated over 40k users, 47% corresponding to students, 35% academia, 9% industry, 5% government, and 4% others (Jain et al. 2018).

MP remarks:

The platform has been able to provide a compositional structure that integrates and formulates analysis for Reactive materials, enabling to branch beyond materials by families (ceramics, glasses, metals, polymers & hybrids). This proposal, mixed with an OER view stimulates curiosity and creation for novel material design.

Material district:



material
district

www.materialdistrict.com

USING MODE	MATERIAL CAT.	MATERIAL CLASS.	COMMUNITY COLLAB.	SUPPLIERS AVAILABILITY	SELECTION PROPERTIES
Free	Inactive, Reactive	Hybrid Eng+Design N	Articles access	No	Environmental, Sensorial & Technical

Figure 58. Material district presentation

Material district is a match-making platform for R&D developers across industries for novel high-end material inspirations.[3]

The platforms stand out by its hybrid proposal as a digital tool, able to combine characteristics of both the informational and inspirational kind, allowing selection by Inspiration and Synthesis means, branching to disciplines, facilitating data to be comprehended by a variety of users.
This same train of thought is used in the 'articles' tab, which aims to actualize the new materials innovation with a simplified, brief review to accelerate knowledge delivery, replying to the Trend desire established previously.

The platform allows selection through keyword searches, material properties, and material categories. It fosters over 3,000 material records, which **indicates the country of origin for the material, linked to the manufacturer, and there is the option to request further information from the provider.**

Figure 59 contains an intervened recreation of the possible parameters and display of information, where the data is not numerically (MP case) but in words and percentages.

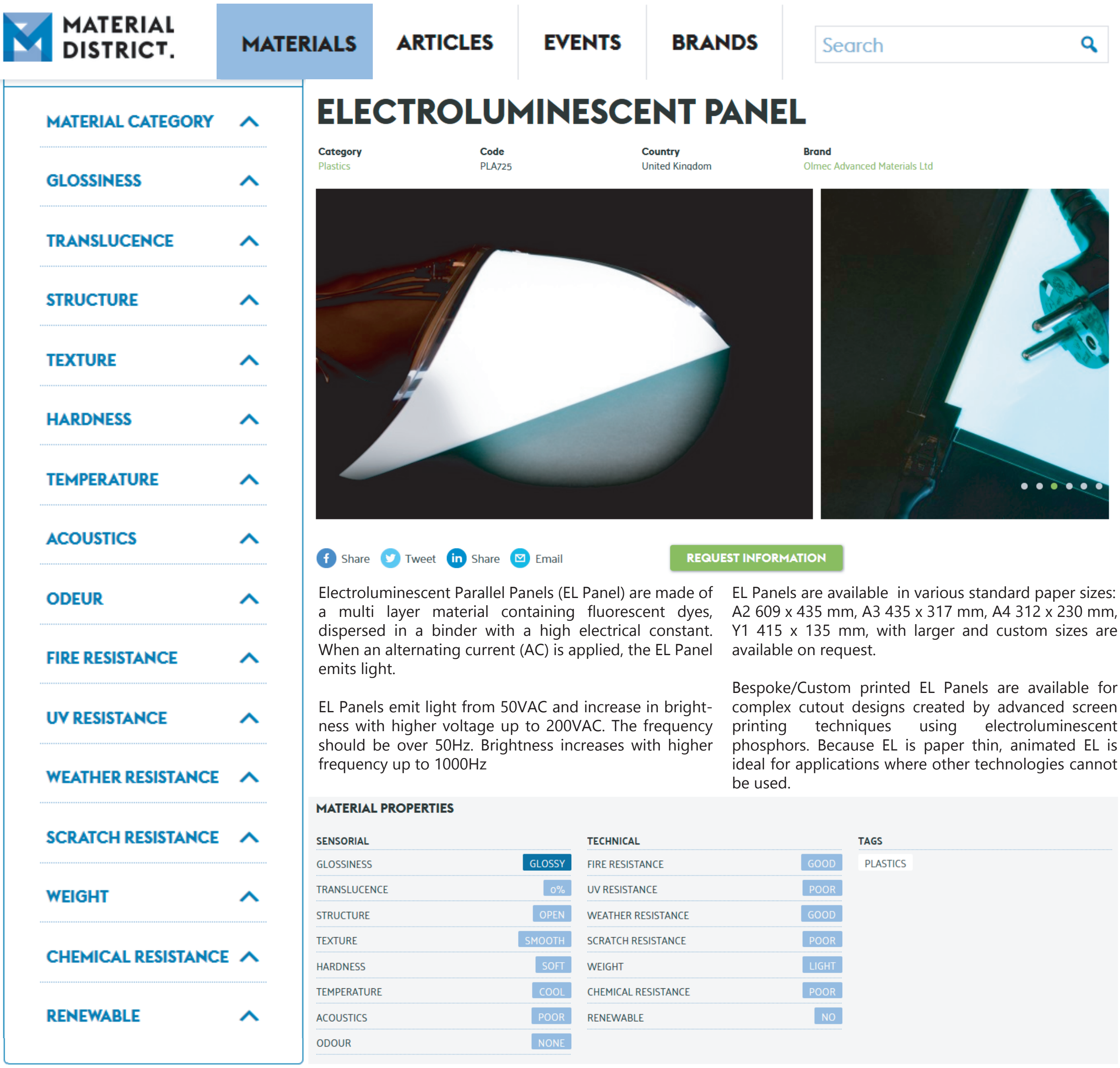


Figure 59. Materials district display of information intervened image

The filter presented at the left corner shows the coverage of the nine material categories, which under this study definition, correspond to material families are, **Ceramics, Coatings, Concretes, Glass, Metal, Natural Stones, Other Naturals, Plastics, and Wood**. The filter also presents technical, sensorial, and environmental properties. Once selecting a specific material, at the first half of the interface, photographs allow familiarization with it, followed by a description that usually contains dimension information and possible applications. At the bottom, the properties of the material are stated organized as either technical or sensorial.

As seen at the top of the photographs there is information regarding the supplier's location and name, complemented by a button under the image that allows to contact them.
There wouldn't seem to be any access to evaluate processes, nor there is a standardization for the information to appear. It can be briefly mentioned in the description of some materials, but not all.

From the 15 material properties displayed at the left, each of them ranges between two to four levels to choose from, as seen in Figure 60.

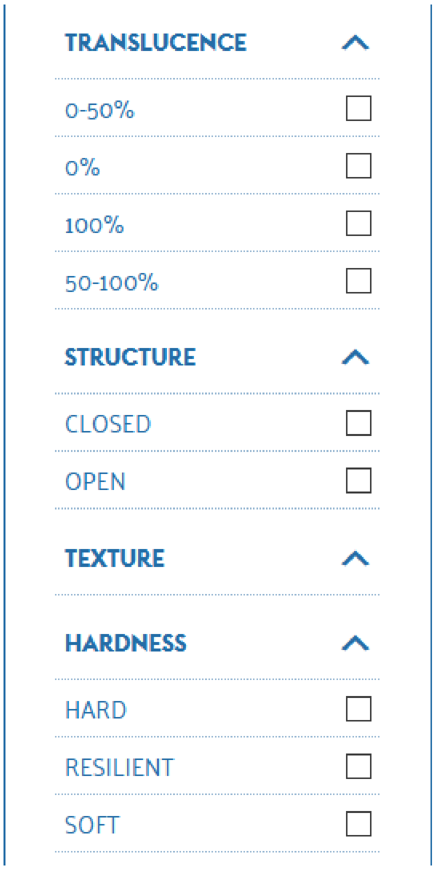


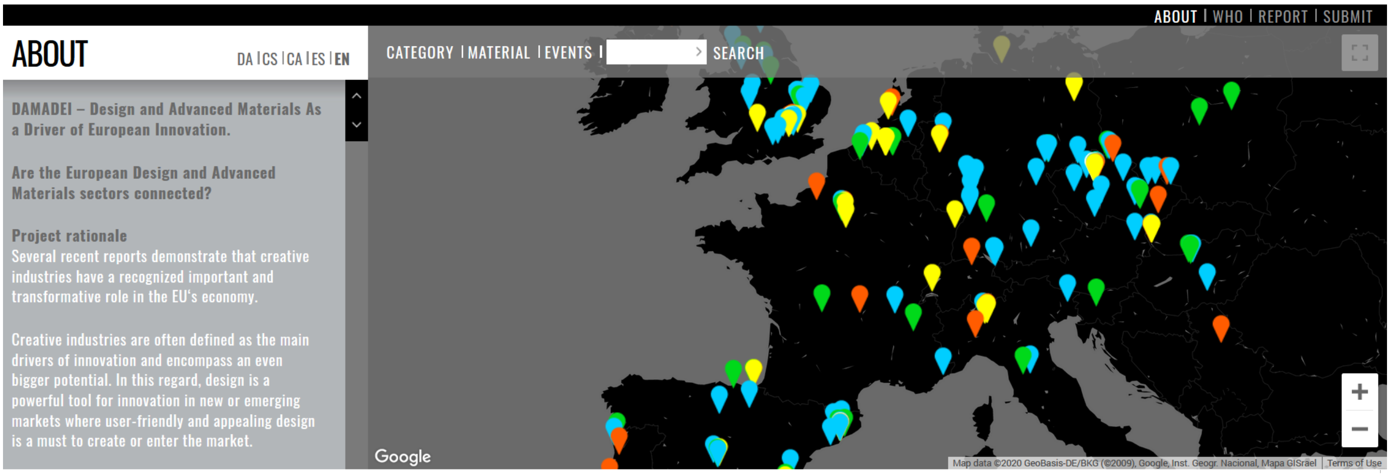
Figure 60. Material district example of ranges, properties levels

This organization would seem to facilitate common language for a variety of users.

Material district remarks:

Through its information architecture and by **simplifying the range in which one can approach the properties**, this framework is a tool for fast search and inspiration. Providing a **common language to the actors' from different disciplines.**

Damadei:



damadei

www.damadei.eu

USING MODE	MATERIAL CAT.	MATERIAL CLASS.	COMMUNITY COLLAB.	SUPPLIERS AVAILABILITY	SELECTION PROPERTIES
Free	Inactive ICS	Inspirational Engineering	Paid consultancy	In EU	Search dependant

Figure 61. Damadei presentation

The Damadei Project is a system to raise awareness among designers to take advantage of the opportunities regarding advanced materials. Its main objective is ***'to consolidate a long-term collaborative European infrastructure to enhance the current network of partners through the involvement of the main European design sector and advanced materials stakeholders.'*** *Mani, 2013*

Damadei looks to promote alliances between the Advance material sector with the Design sector in Europe by analyzing the SWOT of each, aiming to nurture both by fomenting lateral thinking.

Its main contribution has been the recognition of the current market complexity, which response as highly local but increasingly global at the same time, providing a **searcher that enables recognition by zone, type of material, or category of the sector.**

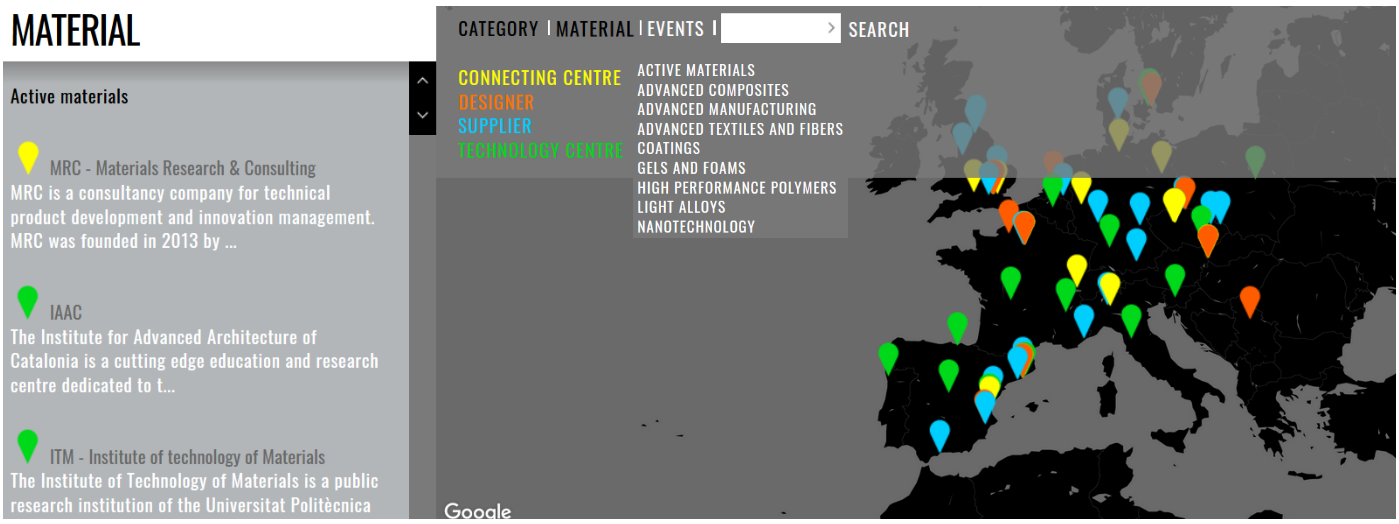


Figure 62. Damadei screen for types of search, intervened image

The database exposes a smart macro-approach to incorporate materials categories focusing on the scope of advanced industry needs and requirements, opposite to MP, which centers the attention purely on a micro-approach without a defined market. Then, the list of materials presents distinction for **Active materials, Advanced composites, Advanced manufacturing, Advanced textile and fibers, Coatings, Gels and foams, High-performance polymers, Light alloys, and Nanotechnology.**

It does not provide information regarding processes, nor current trends in the European market (where the platform centers its data).

Contrary to the other two analyzed applications where there is intervention and control of parameters, Damadei only enables search through filtering the category, material, or events listed in the database, plus an added keyword search. Once selecting the topic, the framework presents on the map the outcomes, listed also at the left bar. Figure 36. contains an example where the search has been established to find 'Suppliers'.

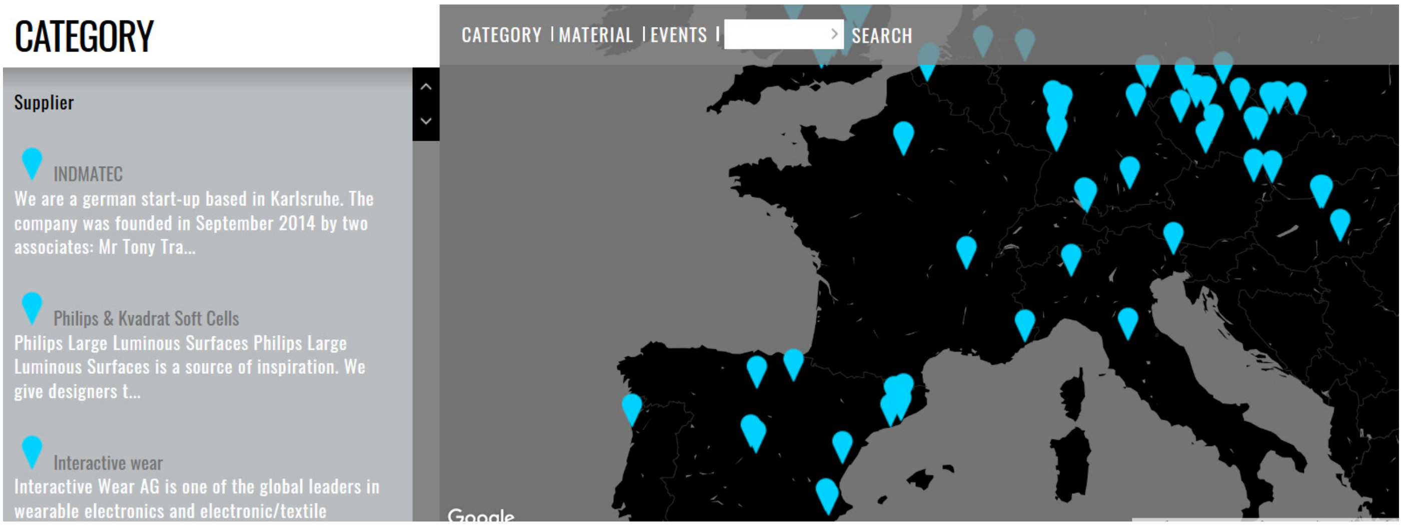


Figure 63. Damadei screen under Suppliers category

Damadei remarks:

This option exploits the **simplification of data, through the use of the graphical design.** By setting a common, visual vocabulary for different disciplines, the platform helps to bridge the gap between material suppliers, designers, and product manufacturers. **Its focus is set on enabling the democratization of knowledge, believing that it can be a medium to potentiate sustainable practices carried by collaboration.**

Matmatch:

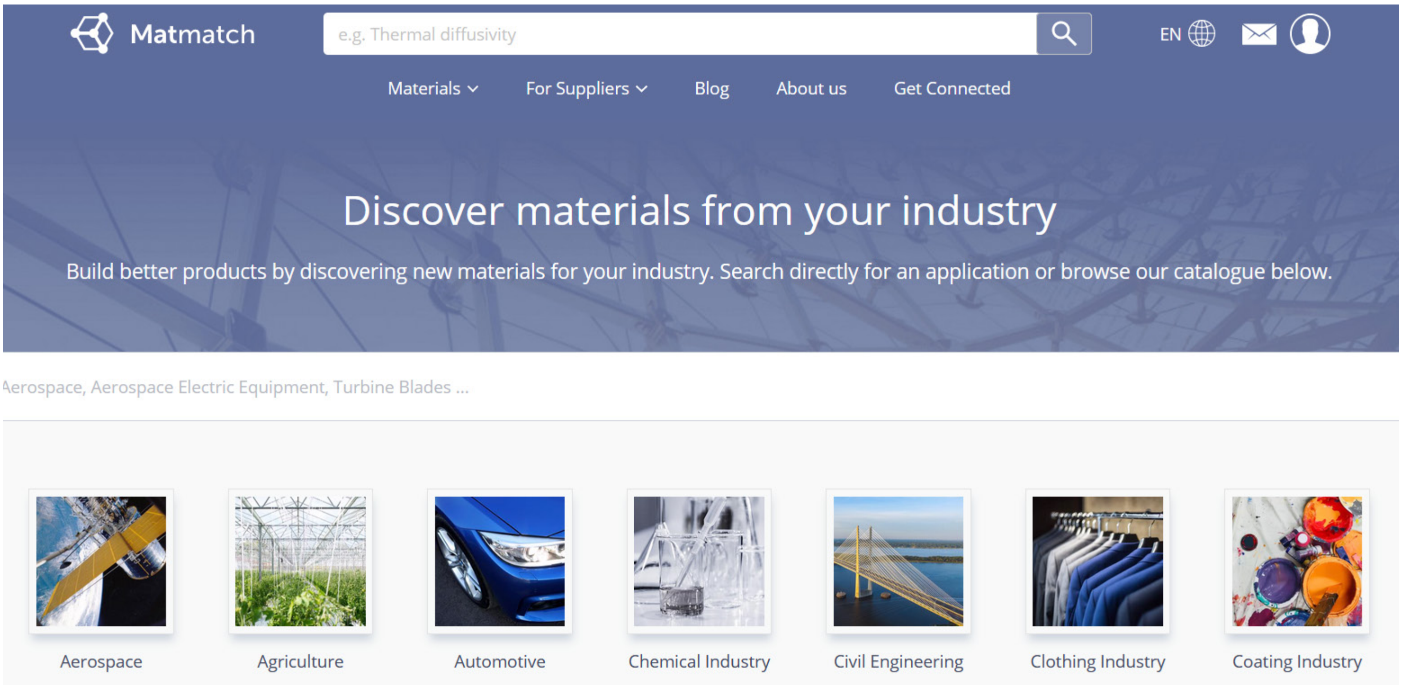


Figure 64. Matmatch screen for application search

Matmatch is a material selector focused on functional variables and Inactive materials. Even though it doesn't meet the established criteria, the platform provides a useful framework organization through its **application search**. This approach enables research from a clear start point with an expected end, **validating the impact a defined path can provide, which wasn´t present in any of the previous platforms.**

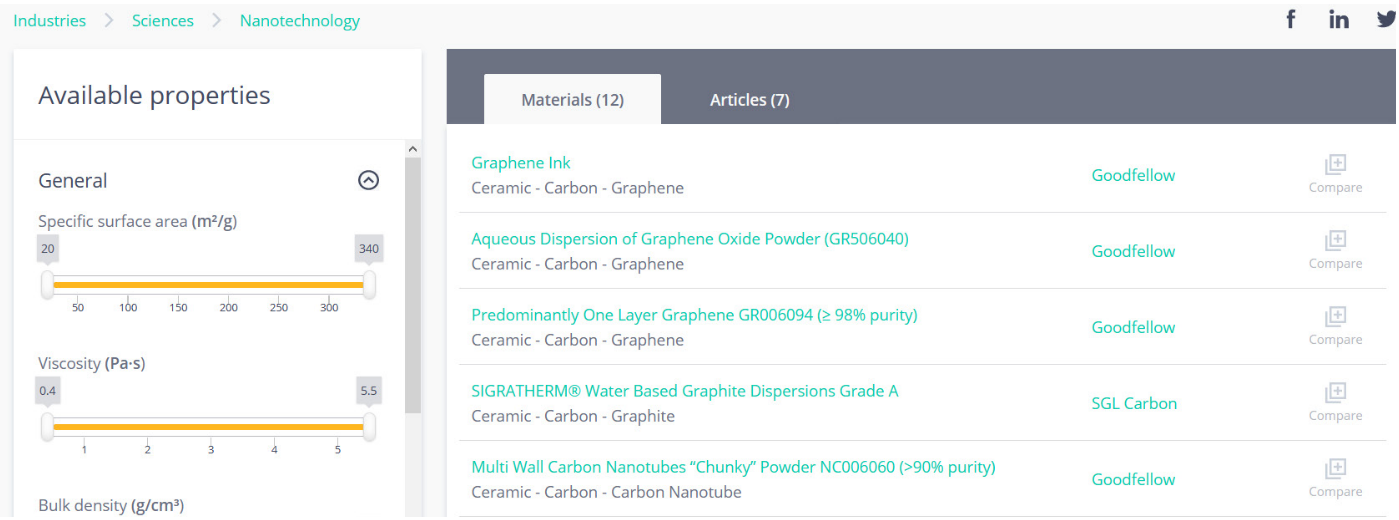


Figure 65. Matmatch screen for application search - nanotechnology

For example, under the topic 'nanotechnology' is possible to acquire information regarding the materials classified for such industry, supported by articles, and allowing an enclosure of the data thanks to the extra filters (at left) according to the project's requirements.

Here the framework structures the information in two novel ways. The first one being able to reduce the data according to parameters inside an already established category, clarifying more and more a possible outcome. Secondary, **allowing to compare materials with a similar purpose.** The result is provided in both textual and graphical ways considering functional properties.

Moreover, the platform responds to a series of market desires, promoting varied services to complement the research and investigation (consultancies and extra tools) for the six categories of materials proposed, **Biological material, Ceramic, Composite, Glass, Polymer, and Metal.**

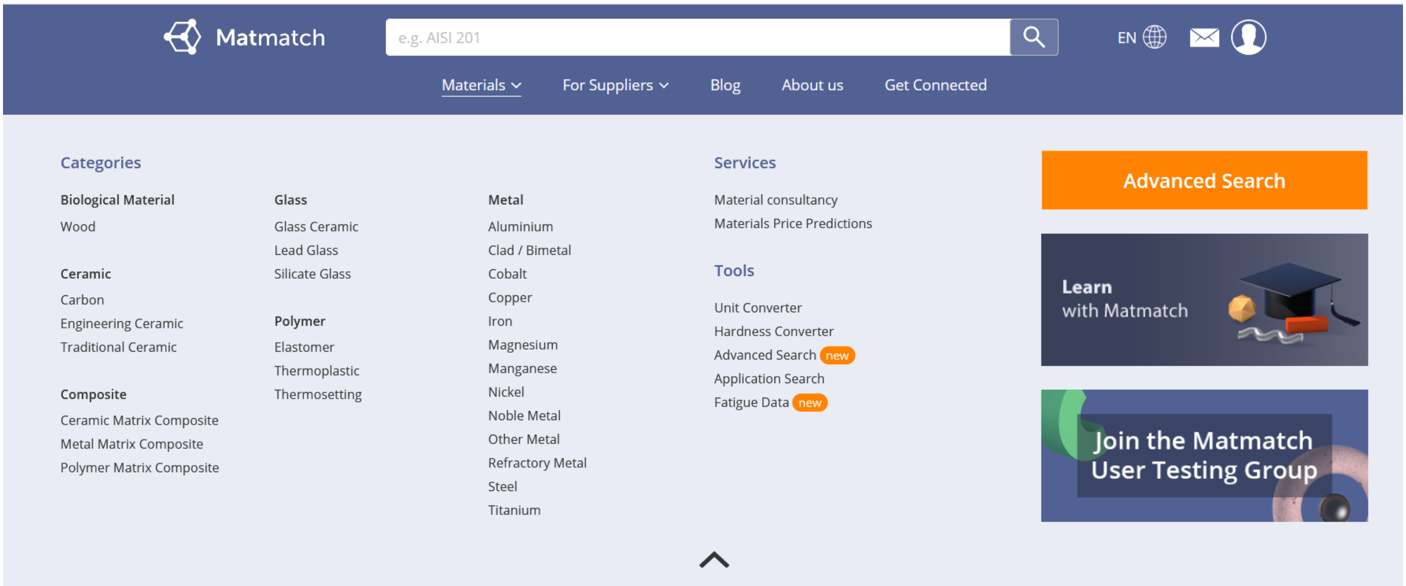


Figure 66. Matmatch screen of material categorie, services, and tools

The platform also presents parameters for processes and supplier considerations once the material family (or category, as mentioned here) is defined. Visible in Figure 40 with and example of Polymer Settings.

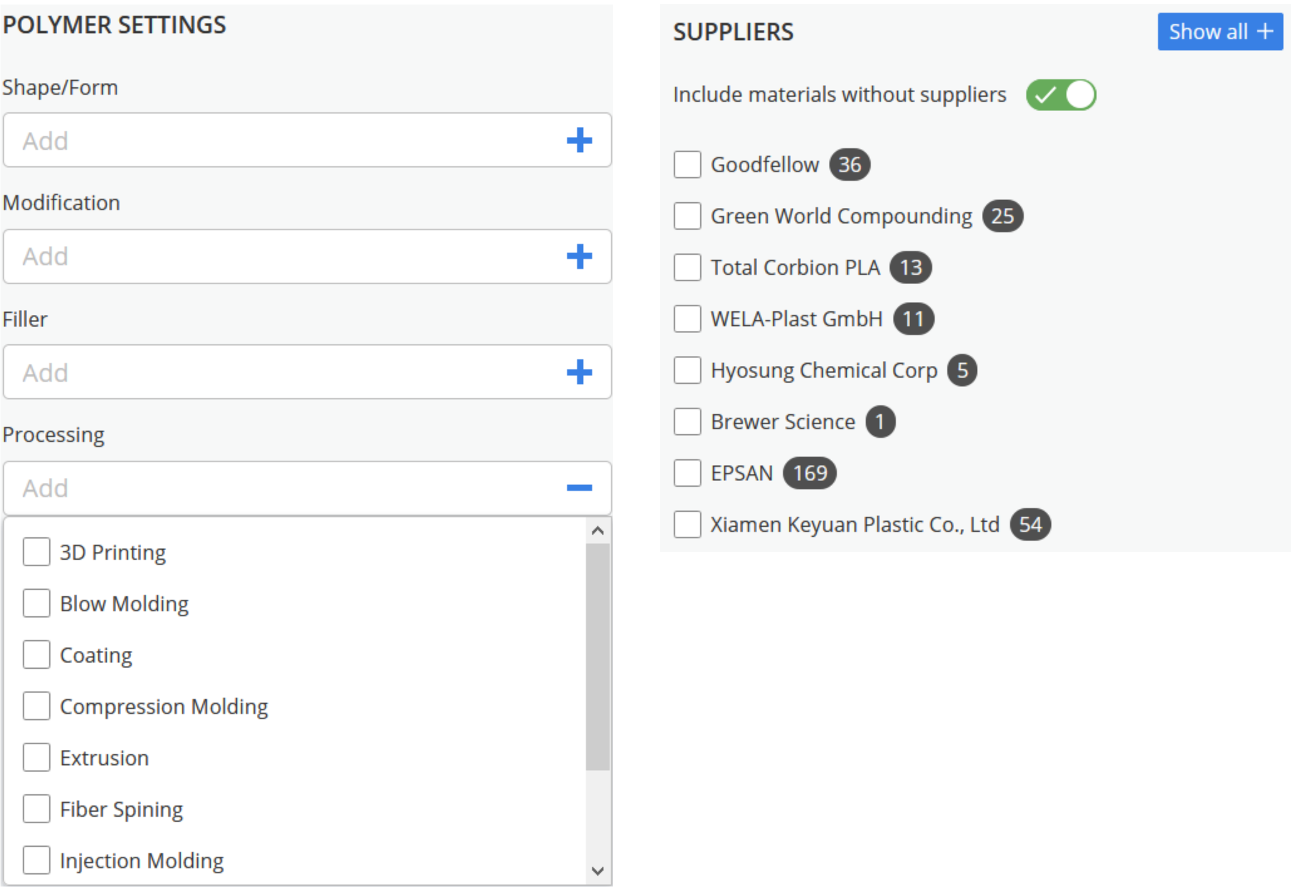


Figure 67. Matmatch screen for processes and suppliers considerationes, intervined image

Matmatch does not provide information about trends on the page, but it does present a wide range of technical properties in its advance search, not presenting considerations for sensorial ones beyond the acoustical, evaluated according to sound speed (longitudinal and transversal).

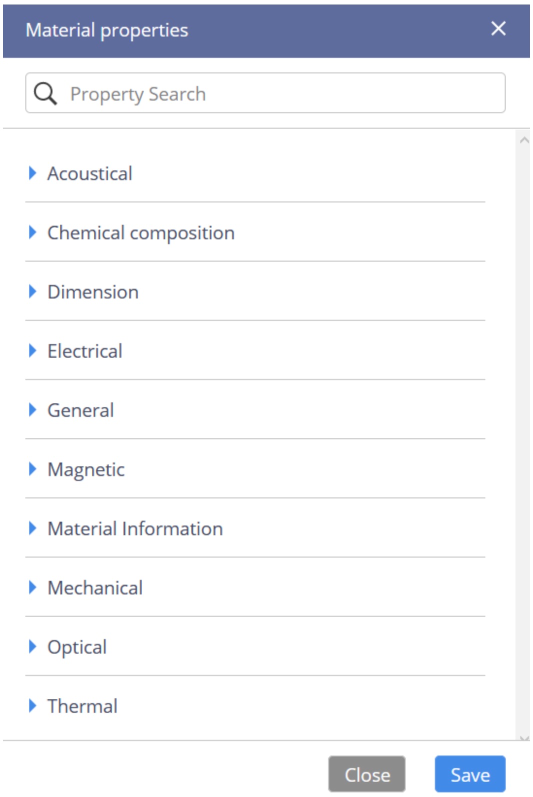


Figure 68. Matmatch screen of technical properties

Matmatch remarks:

This example provides a good visual of funnel information organization and illustrates the clarity it produces when (re)searching for a topic.
Even corresponding to a traditional-dogmatic classification, the platform expands its horizons by exploiting graphical elements that ease the search.

5.2 Result of Database Analysis

Each of the analyzed platforms has proposed novel ways to exhibit materials, trying to simplify a complex multivariable topic, helping to distinguish aspects that are relevant for the outcome platform to work.

Material district and Damadei, both present direct set-ups for their information, where the categories and scopes of the framework are shown since the first tab, facilitating the familiarization with the offered parameters.

Particularly in the case of **Material district, its selected technical and sensorial properties facilitate the research by enabling fast screening according to the project context and requirements**.
The ease to recognize parameters up hand allows a **'free mode' approach, that enables a quick jump to the origin-source for a more in-depth investigation.** This structure can also be seen in Damadei and its categorizations that retrieve the linked suppliers, designers, manufacturers, and innovation centers. The free mode is relevant to enable users' explorations without constraints.

On the contrary, with a more restringed framework, we found the 'application research' section in **Matmatch** that elaborates on the idea of a '**path guide'**, centered around the use scenario for the material, **replacing functional properties by industry categories.** Here we follow a step-by-step approach, where each stage replies to a question e.g. in which industry will the material be used? what technical requirements does it have to accomplish? and so on (see Figures 64 and 65).

From the analyzed platforms it is possible to conclude that there is relevance in providing **technical information disguised as a graphical/interactive one.**
Design professionals often have limited time and skills to invest in user studies (as stated in the pain point on page 124). **The preference toward visual and little text-based representations is interpreted as a common ground for different users to unify language, facilitating content spreading** (Mani, 2013; Karana, Hekkert & Kandachar, 2010; van Kesteren, 2008).

With a different aim and mode, Materials project and its innovative framework for collaborative free research provide a space for materials learning at its core. The page replies to a simulator, enabling in-depth exploration but lacking connection with the materials characteristics that allow to classificate for example possible uses in the market, for this reason it won't be further considered beyond its collaborative structure.

Having detected two different modes useful for exploration (direct set-up for freedom of research, and by industry categories) let's recap on the incorporation of dynamic materials.

As described in Chapters 2 and 4, the differentiation and potential for Reactive and Proactive materials, and particularly for Luminescent ones, fall in is interaction with the user.

From the analysis, it's possible to recognize that all three databases that meet the original criteria seem to be able to or already had, expand their range to include Luminescent materials, but none of the structures fully replies to the parameters of digital era placing materials as the input and experiences as the outcome.

The detected opportunity falls on facilitating an organization that allows versatility of exploration, in order to recognize properties of luminescent materials for defined experiences as the outcome.

As discussed in Chapter 2, Figure 10, interaction is defined by the material formal aspects (form, function, and fabrication), the sensorial stimulus it provides (mainly visual in the case of Luminescent materials), and extrinsic variables such as Intangible properties.

Stressing on the aim to organize and translate information of light-emitting materials aiming to enable active research and acceptance in the product design field, we observe that the information and tools exist but lack either of consideration of parameters or don't fully reply to the current market requirements.

Concluding, the framework should provide a flexible frame to guide the material selection process throughout an established but versatile path, enabling a shared ground of parameters that reply to interaction variables and guide for an outcome experience of Luminescent materials.

5.2.1 General content observations

Thanks to the survey analysis registered at the beginning of the Chapter, we can recognize the desired content required in both EU and SOUTHAM industries, corresponding to:

- **Material categories (Inactive, Reactive, Proactive)**
- **Processes**
- **Trends (Most popular searches in the platform)**
- **Suppliers (With availability by location)**

The expectation is to translate these topics to correlate them with the ones detected from the literature review and market offerings.
Helping to define how to elaborate each, a breakdown of how they were evaluated in the studied platforms is detailed up next.

Materials categories

There is a wide variety for the materials categorization, from not stating one (Materials project) following traditional material families (Matmatch), expanding that base (Material district) to present a new branch (Damadei).

None of the previous uses subclasses of materials, nor differentiates explicitly between the level of interaction at the encounter. Terms of categories such as Inactive, Reactive, Proactive proposed by Rognoli & Garcia (2018), are not presented, providing an opportunity to spread knowledge regarding them. Specifically, there is space to produce a platform that guides on a deep level the use and selection of luminescent materials which can be complemented by presenting more than one search mode.

Properties (directly related to material categories)

The analysis revealed that under the defined criteria, only Material district presents a range of both technical as well as sensorial properties, where the database attributes through properties expressions (e.g. hard, resilient, soft) and simple percentage ratings (e.g. 0%, 0-50%, 50-100%, 100%), this approach would seem to be the clearest one, providing a common language[4].

Processes

In this case, none of the analyzed under-criteria databases presented direct processability information. The only one that incorporates information about it is Matmatch, considering it as a secondary filter that appears once the material family is selected. This topic is aimed to be addressed by the notion of **luminescent forms** as well as grouping project by industries as described in section 2.3.3

Suppliers (with availability by location)

The analysis stated that only Damadei considers location as a remark variable. Unfortunately, this approach is restricted only to EU-selected suppliers, and there is no information regarding when was the list last update.
Material district informs about the country of origin of the material and connects with the supplier to obtain further information, but is not as direct and clear as the information displayed in the first-mentioned database.

4 As mentioned in page 110, under the statement of Mani (2013).

This particular aspect is not directly related to the parameters studied in the layers chapters, nor none of the analyzed databases stated the commercial availability of the materials. Due to the complexity to connect and further obtain information regarding the topic, **this aspect will not be incorporated in the database framework.**

Trends (most popular searches in the platform)

This particular aspect correlates to the notion of users guiding their work from collaborative means, searching to build upon the knowledge or projects of others. Unfortunately, none of the studied platforms stated clearly the most seen materials, most researched keywords, or similar. **This aspect will be considered as an extra, once the primordial aspects of the framework have been developed.**

To conclude on the general aspects, a summary of the opportunities detected through each study is stated in Figure 69.

Objective: Propose an OER platform framework designed to support and guide the selection of luminescent materials under the parameters of the digital era (i.e. open educational resource and experience focused) for students an early practitioners of the product design field.

LITERATURE REVIEW

Must respond to material interaction variables (functional-hedonic means)

Must be open access (OER)

Must be experience oriented

USERS NEEDS

Clarify on dynamic potentialities

Guide on decision-making

Direct set up to provide versality of search

DATABASE ANALYSIS

Research under a 'path mode' such as by industry

Shared language for attributes properties expressions and simple percentage ratings

Figure 69. Conclusion of opportunity detection

The specific parameters and properties to be incorporated into the platform are discussed up next.

5.2.2 Specific content observations

Parameters and criteria that define luminescent materials in their functional-hedonic means have been selected from the information proportionated by the case studies analyzed in section 2.3.4. These properties have been compiled and complemented with the results of the earlier conducted literature review and database analysis.
The list with 3 general parameters, 7 functional, and 7 hedonic ones is defined as follows:

General Parameters

Provide an entry guideline of characteristics for the desired material which reverberates both in the functional and hedonic parameters.

Support material: Material(s) with who the luminescent component will be mixed, deposited on or accompanied by, defined according to the case studies terms, and complemented by the database analysis. More than one option can be marked:

- Metals
- Polymers
- Natural fibers
- Concrete
- Glass
- Ceramics

Scale of material/project: Range of dimension in terms of possible application. Based on case studies information, complemented by the scale proposition presented by Hölter (2019):

- Millimeter scale (mm),
- Millimeter to centimeter scale (mm-cm)
- Centimeter scale (cm)
- Centimeter to meter scale (cm-m)
- Meter scale (m)

Luminescent effiency: Brightness obtained by dividing the source's luminous flux by the consumption of its energy. This parameter has been defined in page 57, used to defined luminescent materials in general terms, but hard to find for individual cases. Proposed for its relevance in the matter when picking a light-emitting material. Presented in percentage ranges:

- 0-25%
- 25-50%
- 50-75%
- 75-100%

Functional Parameters

Mode of excitation: Refers to the mode of energy that works as the initiator for the transformation of the material (i.e. input stimulus). The relevance of recognizing this parameter relates to being able to select the material that best fits the needs according to the industry of application, color emission, and modularity (Addington & Schodek; 2005; Lefebvre et al. 2014; Bergamaschi et al., 2016; Papile et al. 2019). Five input stimuli have been selected throughout this thesis due to their relevance in several industries complemented by accessible information of each, corresponding to:

- Chemical reaction
- Biochemical reaction
- Absorption of light
- Frictional and electrostatic forces
- Electric field

Type of luminescence: As a direct response to the mode of excitation, per each mode, there is (at least) one luminescent phenomenon, defined according to the input stimulus. The five selected types correspond to:

- Chemiluminescence (CL)
- Bioluminescence (BL)
- Photoluminescence (PL)
- Mechanolumiescence (ML)
- Electroluminescence (EL)

Each type is characterized differently, variating in the frequency of supply needed, transformation speed, emission duration, color availability, to name a few. All of these parameters define the material individually, but also can guide the selection according to the needed application and the type general characteristics (see Figure 18), as technology advances provided a wider variety of spectrum for ones more than others.

Frequency of supply: Establishes in general terms the power needs the material requires to produce light emission. This parameter is an analog of the one established by Coelho and Zigelbaum (Coelho and Zigelbaum, 2011) for SCMS, where they define the concept 'Power requirement' as the requested for the initiation/actuation of the material.
After consideration and evaluation of the case studies where there is a wide variety of scenarios, the parameter has been defined to range between:

- Intermittent: supply is needed a limited number of times for light emission.
- Constant: requires several/fluid supply to emit light.

Transformation speed: Time needed for the effect to occur from the moment the input is received (Papile et al. 2019). This notion is based on the proposals from Coelho and Zigelbaum (2011); Follmer (2015); and Lefebvre et al., (2015), taking as guidance some of the ranges defined by Höelter (2019):

- Instant (seconds)
- Delayed (seconds-minutes)
- Long-delayed (minutes - hours)

Emission duration: Refers to the time needed for the material to turn back to its initial state (i.e. duration on which the material is in its temporal form). Comes from the notion of 'relaxation time' defined by Papile et al. (2019). Presented in the same ranges as transformation speed:

- Instant (seconds)
- Delayed (seconds-minutes)
- Long-delayed (minutes - hours)

Reversible change: Ability of the material to shift from its original physical form to its temporal one and vice-versa. Connected to the notion of the material's self-recovery or recovery speed discussed by Lefebvre et al., (2015). The possibilities are:

- Yes (the material can go back and forward in its forms by itself)
- No (the change can occur only in one direction)

Luminescent form: Shape on which the luminescent component is carried or deposited over the support material (support materials can be metals, polymers, wood, etc, see Table 5). This particular parameter was elaborated in section 2.3.3 in the search to understand the fabrication processes involved to generate a variety of functions for light-emitting materials. Concluded options are:

- Powder
- Liquids & gels
- Thin films
- Fibers & filaments
- SSL (Solid State Lighting)
- Bio-organisms

Hedonic Parameters

The first four hedonic parameters correspond to visual sensory properties, previously defined by Karana (2009); Zuo (2010), based on the intensity ranges presented by Piselli et al. (2018), and complemented in scale with terms observed in the database analysis section.

Glossiness: Ability of a material to reflect light in a specular (mirror-like) direction. Ranges between:

-Glossy
-Satin
-Matte

Transparency: Materials capacity to allow light to pass through it without an appreciable scattering of light.

-Transparent
-Translucent
-Opaque

Color intensity: Refers to the degree of purity of a color, also known as color saturation or chroma.

-Bright
-Dim
-Dull

Surface evenness: Refers to the outer layer of the material and the deviations it presents.

-Regular (smooth)
-Irregular (rough)

Direction of light-spread: Related to the luminescent form (as shown in Figure 44), covers in general terms the degrees on which the emitted light would be visible to the human eye according to the type of form source.

- Point source (under 170°)
- Surface source (around 170°)
- All directions (360°)

Type of change: Related to the functional parameter 'Reversible change' and responds to the subparameters defined by Papile et al. (2019). The possibilities comprehend:

-Single change: one change occurs at a precise value of the input, giving the material two states between which it switches
-Continuous change: the change is gradual occurs between two values of the input
-Multiple changes: several changes can occur at precise values of the input

Mode of interaction: Based on the proposal presented by Rasmussen (2012) and adapted for the work of luminescent materials, this parameter evaluates the necessity of physical involvement of a person for the material to produce change. Differentiating between:

-No interaction: Change occurs without the intervention of a person
-Indirect: Change is produced by an implicit input generated by a person
-Direct: Change is produced by the explicit and intentional physical involvement of a person.

A secondary set of parameters for the Hedonic group is still missing to be defined, corresponding to the Intangible ones. To recognize them a study was carried via an online questionnaire[5] to observe users' perceptions and associations from the projects to defined keywords.

Six case studies (extracted from the selection displayed in section 2.3.3, one per each luminescent form) were presented in graphical cards to 31 product design students and early practitioners with an age range from 18 to 39 years old, and from nine different nationalities[6] (EEUU, Chile, Argentina, Egypt, Italy, France, Germany, India and China).
For each card, users were asked to select a maximum of four attributes from the lists of interpretive and affective levels developed by Camera and Karana (2018) (see Tables 1 & 2). This study aimed to evaluate if the lists are a resourceful tool to implement in the platform, or they could be shortened.

5 To see the questionnaire, please refer to the Annex, page 155.
6 To check the answers in detail, please visit the **following link**.

The selected cases corresponded to:

- For the powder form, case n° 6 - Light-emitting cement
- Liquid solutions & gels, case n° 7 - ML paint
- Thin films, case n° 12 - VynEL
- Fiber & filaments, a complement of case n° 11 - ML fiber
- SSL, case n° 3, Luminous Textiles
- Bio-organisms, case n° 16, BIO.tech HUT

The cases were displayed without a defined order, followed by the two sets of lists for users to select according to their perception of the projects. An example of the cards can be observed in Figure 70.

Light Emitting Cement

Self-luminescent cement-based composite materials (SLCCM) for environmental protection, smart pavement

Luminous efficiency: Unknown

Functional aspects	
Parameter	**Response**
Mode of excitation	Absorption of light
Frequency of supply	Intermittent
Transformation speed	Delayed (seconds - minutes)
Emission duration	Long-delayed decay (minutes-hours)
Reversible change	Yes
Luminescent form	Powder

Hedonic aspects	
Parameter	**Response**
Glossiness	Matte
Transparency	Opaque
Color intensity	Bright
Surface eveness	Irregular
Type of change (S/C/M)	Single
Direction of light-spread	Surface source (170°)

Figure 70. Example of cards used for intangible keywords evaluation

After providing recognition of the cases, the users' were asked to select a maximum of four keywords per case, the general results are as follows:

From the original **Interpretetive list**:

- Aggressive, Calm, Cozy, Aloof, Elegant, Vulgar, Frivolous, Sober, Futuristic, Nostalgic, Masculine, Feminine, Ordinary, Strange, Sexy, Not sexy, Toy-like, Professional, Natural, Unnatural, Hand-crafted, Manufactured.

All keywords were selected at least per one of the cases, **prevailing preference in concepts** such as **Futuristic**, and **Elegance**, while Vulgar and Ordinary were the least selected in almost all cases.

For the **Affective level,** with keywords being:

- **Love, Frustration, Amusement, Boredom, Surprise, Disappointment, Confidence, Reluctance, Enchantment, Confusion, Respect, Rejection, Attraction, Disgust, Curiosity, Melancholy, Fascination, Distrust, Comfort, Doubt.**

Concepts such as **Curiosity** and **Attraction** were the preferred ones to describe the cases, while Frustration and Disgust were the least preferred of the bunch.

From the study it's possible to conclude **the lists are useful to describe and characterize projects under known terms for users from different nationalities, providing a helpful tool for the valorization of projects, and guidance for research** (e.g. search for Futuristic, Toy-like, Curiosity keywords, and obtain several luminescent projects that accommodate to those descriptions).

Moreover, it was possible to confirm a hypothesis discussed previously on thesis reviews, suggesting that **the selection of concepts varies according to demographics**. An example of this is the selection of **interpretive vocabulary for case n°16**, **where the biggest national groups** (Chile, with a total of 13 responses, versus Italy with a total of 10) **were compared, displaying a pattern for both groups,**

-Chileans presented a more scattered appreciation of the project with an agreement of 8 of them evaluating it as Futuristic, followed by the concept Natural. **Italy** on the other hand, displayed **absolute congruency on the concept of Natural,** followed by the concept Futuristic a notion that prevailed when evaluating other close European countries' responses.

-Even though in some cases the selection is not so evident, **most cases present at least one clear concept that stands out per nationality or habitat group.** Another example is case n°3, which got marked 8 times in the Affective level as Attraction by Chileans, while the preference for Italians, with 6 marks, was the concept of Amusement.

Is by this study that it is possible to determine that the parameters to evaluate the intangible aspects of the materials will correspond to:

Intangible parameters

Targeted demographics: Users on which selected emotions are desired to be produced.

- Age group: Refers to the people to who the product or material is designed for. Based on the structure presented by Ritchie & Roser (2019), and complemented by personal insight.

- Infant (0 - 4 y.o)
- Young Child (5 - 12 y.o)
- Adolescent (13 - 19 y.o)
- Young adult (20 - 35 y.o)
- Adult (36 - 64 y.o)
- Senior (65 - 85 y.o)
- Elder + (over 85 y.o)

-Region or country desired to address: To be specified according to continents or countries.

With 45.2% of the responses provided by males and 54.8% by females, it wasn't possible to conclude differentiations on the selection of concepts, for this reason, gender is not a part of the Intangible parameters selected for this study.

Experience auxiliary: Interpretive and Affective vocabulary to support the communication of the desired experience. Based on the lists generated by Camera and Karana (2018). The selection of the auxiliary terms should not exceed a total of 4.

- **Interpretive list**: How materials can be perceived

    - Aggressive, Calm, Cozy, Aloof, Elegant, Vulgar, Frivolous, Sober, Futuristic, Nostalgic, Masculine, Feminine, Ordinary, Strange, Sexy, Not sexy, Toy-like, Professional, Natural, Unnatural, Hand-crafted, Manufactured.

- **Affective list**: How materials can make us feel

    - Love, Frustration, Amusement, Boredom, Surprise, Disappointment, Confidence, Reluctance, Enchantment, Confusion, Respect, Rejection, Attraction, Disgust, Curiosity, Melancholy, Fascination, Distrust, Comfort, Doubt.

Search by Industry:

Finally, replying to the market's need and offerings concluded by the platform analysis, the parameters defined for the proposal are:

Industry of application: Search mode according to categories for the desired application. These are defined according to the results obtained in section 2.3.3 and follow the idea presented by Matmatch (see Figure 64).

- Energy
- Electronics
- Construction
- Healthcare
- Textiles
- Defense & Security
- Agriculture

Having defined the sets of parameters for the platform to provide as a decision-making method for luminescent materials, it is possible to start the development of it.

Chapter summary

Information retrieved from literature targeted users, and market competitors have been the elements selected to study and detect opportunities that could facilitate the acceptance of luminescent materials and their selection in the product design field.

The information correlates on aspects such as the need for flexibility of research, that could be supported by decision-making methods and exploration, providing a guided approach on the potentialities of dynamic-luminescent materials and their potentialities to facilitate their shared knowledge.

Moreover, as a mode of conclusion, it is possible to see that the platform must provide information regarding the functional-hedonic parameters, promoting the notion that properties recognition can help recognize patterns generated in users, amplifying or diminishing the desired experience of products.

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Chapter 6:

Database framework

'What we need, especially when working with new forms of interactive materials, is to devise ways of bringing the materials into the explorations earlier in the design process, and also make them a shared resource for everyone involved, e.g., designers, developers, engineers, HCI-experts, dancers, psychologists, and end-users.'

Fernaeus & Sundström, 2012

6. Database framework

With the always-changing field of product design, such as new holistic approaches in branches like materials selection, and the impact sensorial language can have in the interaction carried by product-user, is that the main objective of this thesis is to **propose a framework of a database focused on guide, connect and enable the growth of luminescent material and projects in the product design field.**

The need for this kind of tool, experience- as well as -decision-making-oriented can be observed along with the evolution of product design didactics (Chapter 1), the intersection of design and material science, exemplified by case studies (Chapter 2), the pain points detected in materials selection methodologies (Chapter 3), contrasted and validated by the markets needs and offerings in regards of platforms for dynamic materials retrieve of information (Chapter 5). Through them all, it was possible to articulate a set of parameters and properties specific for Luminescent materials (expressed at the end of Chapter 5).

Replying to the requirements of the digital era and as a solution to the pain points detected throughout this research, the platform is an OER tool designed to contain, transmit and help the growth of luminescent projects through the recognition of specific functional and hedonic (including intangible) parameters to respond to the full spectrum of interaction variables (see Figure 10).

The database analysis detected opportunities to improve the search experience by presenting more than one search mode (by properties and by industry) grouping parameters in distributions that would facilitate their selection, allowing versatility of exploration allowing to (but not exceptionally) obtain experiences as outcomes. Enabling then a framework able to provide versatility for the users' search of resources.

The platform is proposed with three main areas of research/evaluation, implementing, besides the search modes, a tab destined for users to upload projects or evaluate others according to their Intangible parameters (Age group, Region or country of origin, Interpretive and Affective sets of lists), providing recirculation of knowledge and enable the users' to participate in different levels (as researchers, evaluators, or project's submitters).

Considering the overall evaluation of this thesis is to support and guide the incorporation of **Luminescent Materials** in the field, which corresponds to dynamic materials able to change their physical form into a temporal one by emitting-light and, in most of the cases, return to their original state, is that the platform is named **Flux of light**.

6.1 Flux of light: Database structure

The database is centered around the ‘Property search’, which groups the general, functional, and hedonic parameters for users to select according to their needs and expected outcome experience, Moreover, two other main tabs are selectable, corresponding to ‘Search by industry’ and ‘Get involved!’, as well as a tab destined to provide general information regarding what is luminescence, it’s functional principle and potentialities of use.

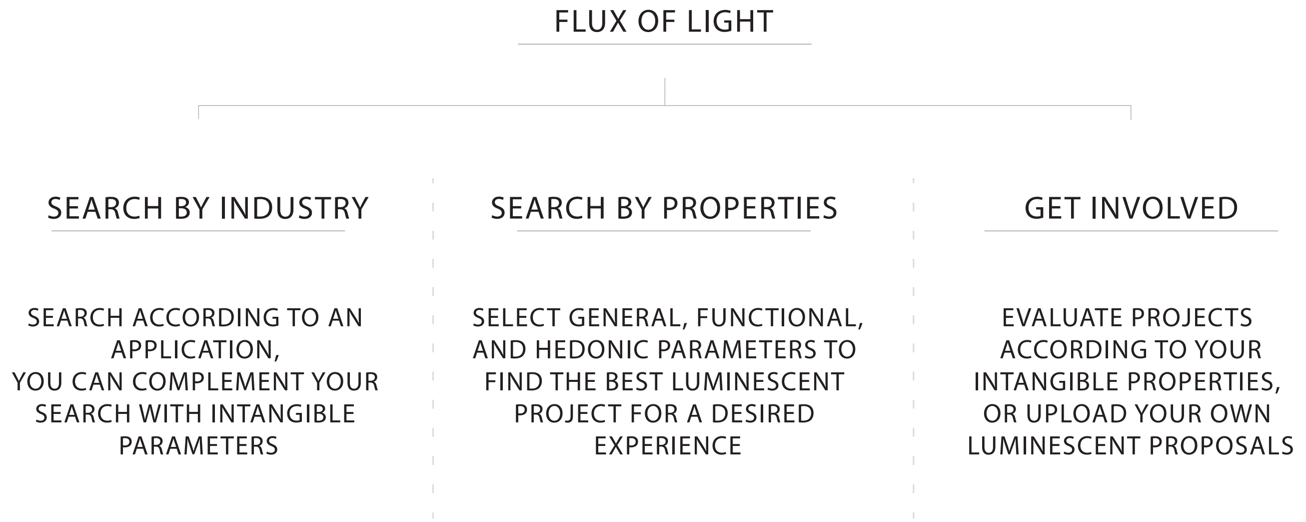


Figure 71. Framework distribution of Flux of light

Each section access individual material records according to the requested parameters, while the ‘Get involved!’ section feeds on new data for the platform to grow in information.
The search modes permit the user to get more in-depth knowledge according to their needs while approximating properties in a fuller way. This approach will allow exploration of luminescent materials, enabling collaboration between peers.

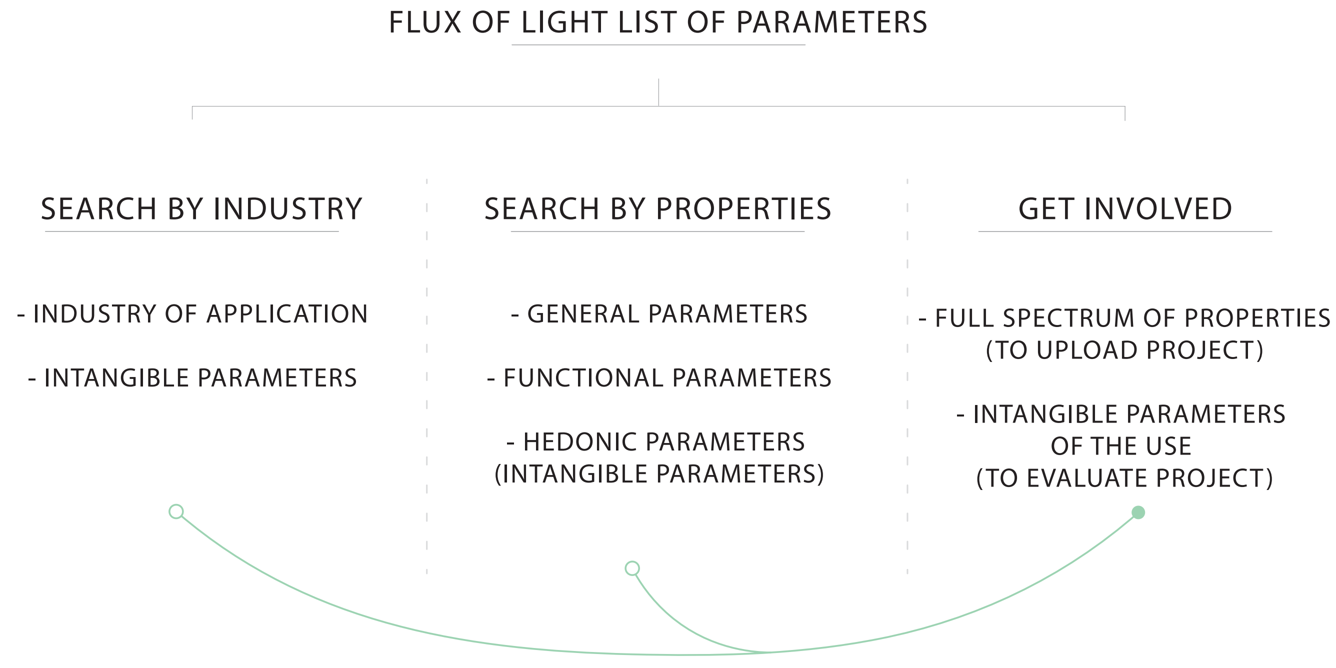


Figure 72. Flux of light list of parameters

6.2 Flux of light: Database content

The content of properties per each search and evaluation mode is displayed in the following images according to the definitions described in section 5.2.2.

For 'Property search' the distribution has been designed to achieve experiences as the outcome, by redistributing the content based on the notion of Dorst (2002) 'what' +'how' leads to 'value'.

PROPERTY SEARCH

GENERAL

- SCALE OF MAT/PROJECT:

Millimeter (mm)
Millimeter to centimeter (mm-cm)
Centimeter (cm)
Centimeter to meter (cm-m)
Meter (m)

- SUPPORT MATERIAL:

Metals
Polymers
Natural fibers
Concrete
Glass
Ceramics

- LUMINESCENT EFFICIENCY:

0-25%
25-50%
50-75%
75-100%

- INTANGIBLE PARAMETERS:

Age group:
Infant (0 - 4 y.o)
Young Child (5 - 12 y.o)
Adolescent (13 - 19 y.o)
Young adult (20 - 35 y.o)
Adult (36 - 64 y.o)
Senior (65 - 85 y.o)
Elder + (over 85 y.o)

Region or country desired to address

Affective & Interpretive lists

FUNCTIONAL

- MODE OF EXCITATION:

Chemical reaction
Biochemical reaction
Absorption of light
Frictional and electrostatic forces
Electric field

- TYPE OF LUMINESCENCE:

Chemiluminescence (CL)
Bioluminescence (BL)
Photoluminescence (PL)
Mechanolumiescence (ML)
Electroluminescence (EL)

- FREQUENCY OF SUPPLY:

Intermittent
Constant

- TRANSFORMATION SPEED:

Instant (seconds)
Delayed (seconds-minutes)
Long-delayed (minutes - hours)

- EMISSION DURATION:

Instant (seconds)
Delayed (seconds-minutes)
Long-delayed (minutes - hours)

- REVERSIBLE CHANGE:

Yes
No

- LUMINESCENT FORM:

Powder
Liquids & gels
Thin films
Fibers & filaments
SSL (Solid State Lighting)
Bio-organisms

HEDONIC

- GLOSSINESS:

Glossy
Satin
Matte

- TRANSPARENCY:

Transparent
Translucent
Opaque

- COLOR INTENSITY:

Bright
Dim
Dull

- SURFACE EVENNESS:

Regular (smooth)
Irregular (rough)

- DIRECTION OF LIGHT-SPREAD:

Point source (under 170°)
Surface source (around 170°)
All directions (360°)

- TYPE OF CHANGE:

Single change
Continuous change
Multiple changes

- MODE OF INTERACTION:

No interaction
Indirect
Direct

→ WHO, WHERE & WHY → WHAT → HOW → *Value*

Figure 73. Property search content and distribution

SEARCH BY INDUSTRY

CATEGORIES

Energy
Electronics
Construction
Healthcare
Textiles
Defense & Security
Agriculture

COMPLEMENTS

- SCALE OF MAT/PROJECT:

Millimeter (mm)
Millimeter to centimeter (mm-cm)
Centimeter (cm)
Centimeter to meter (cm-m)
Meter (m)

- SUPPORT MATERIAL:

Metals
Polymers
Natural fibers
Concrete
Glass
Ceramics

- LUMINESCENT EFFICIENCY:

0-25%
25-50%
50-75%
75-100%

- INTANGIBLE PARAMETERS:

Age group:
Infant (0 - 4 y.o)
Young Child (5 - 12 y.o)
Adolescent (13 - 19 y.o)
Young adult (20 - 35 y.o)
Adult (36 - 64 y.o)
Senior (65 - 85 y.o)
Elder + (over 85 y.o)

Region or country desired to address

Affective & Interpretive lists

WHERE → WHO & WHY → *Value*

Figure 74. Industry search content and distribution

On the other hand, simplified in its parameters, 'Search by Industry' aims to provide fast feedback of possible materials or projects according to the thought application. The search mode is complemented by general and intangible properties to provide context, connect patterns while following the baseline of the platform.

Finally, the content for the 'Get involve' tab depends on the action made by the user. The description of properties follows the same order described in the two previous images.

GET INVOLVE

EVALUATE

- INTANGIBLE PARAMETERS:

Age group:
Infant (0 - 4 y.o)
Young Child (5 - 12 y.o)
Adolescent (13 - 19 y.o)
Young adult (20 - 35 y.o)
Adult (36 - 64 y.o)
Senior (65 - 85 y.o)
Elder + (over 85 y.o)

Region or country desired to address

Affective & Interpretive lists

UPLOAD

- GENERAL PARAMETERS

- FUNCTIONAL PARAMETERS

- HEDONIC PARAMETERS

Figure 75. Get involve content and distribution

The path followed for each mode is graphically presented in the sections to come.

6.2.1 Property search

When accessing the Flux of Light platform, the user accesses the entry for 'Property search', with the possibility to shift to the other two available modes, as displayed in Figure 77.

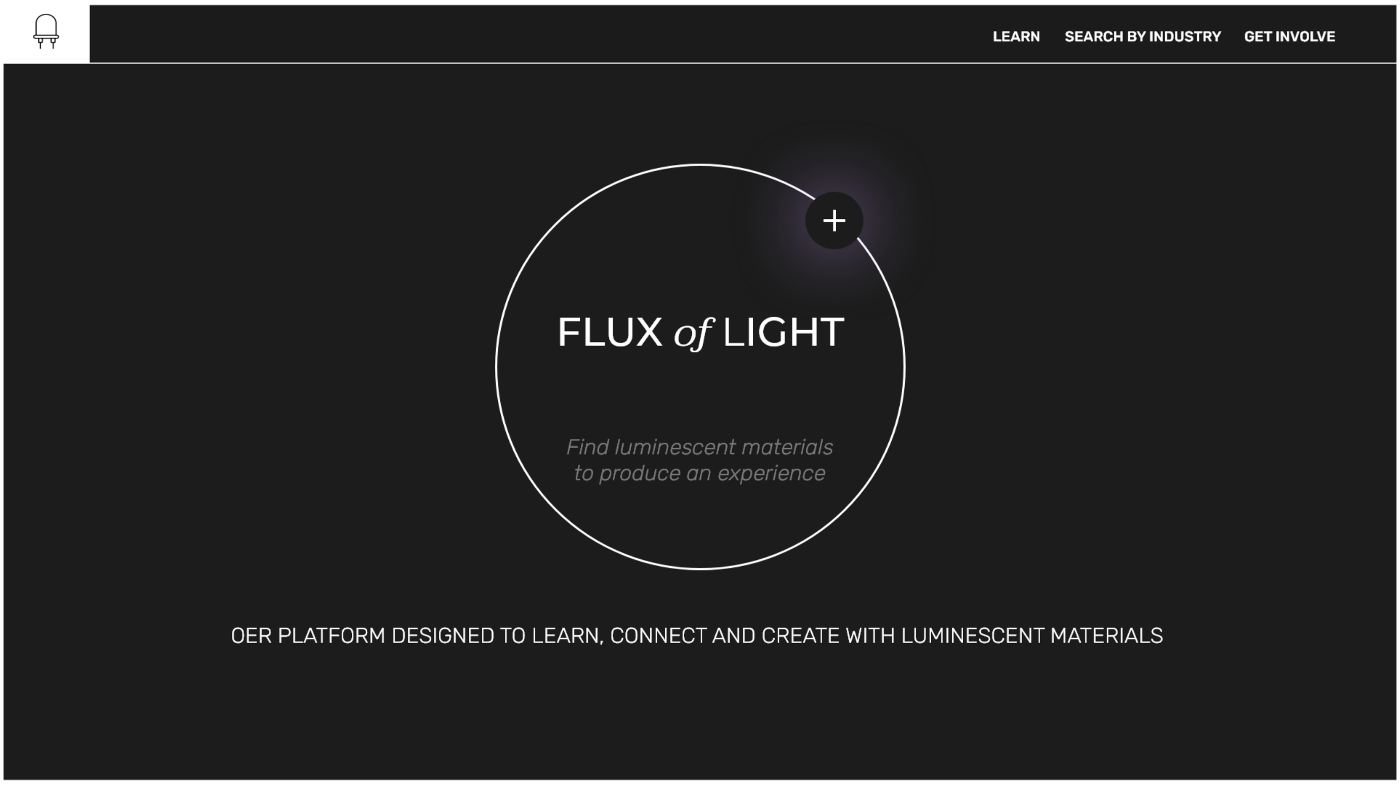


Figure 76. Home screen of Flux of light

Once starting the research at the property database the three main groups of parameters (General, Functional & Hedonic) are displayed enabling the user to evaluate freely.

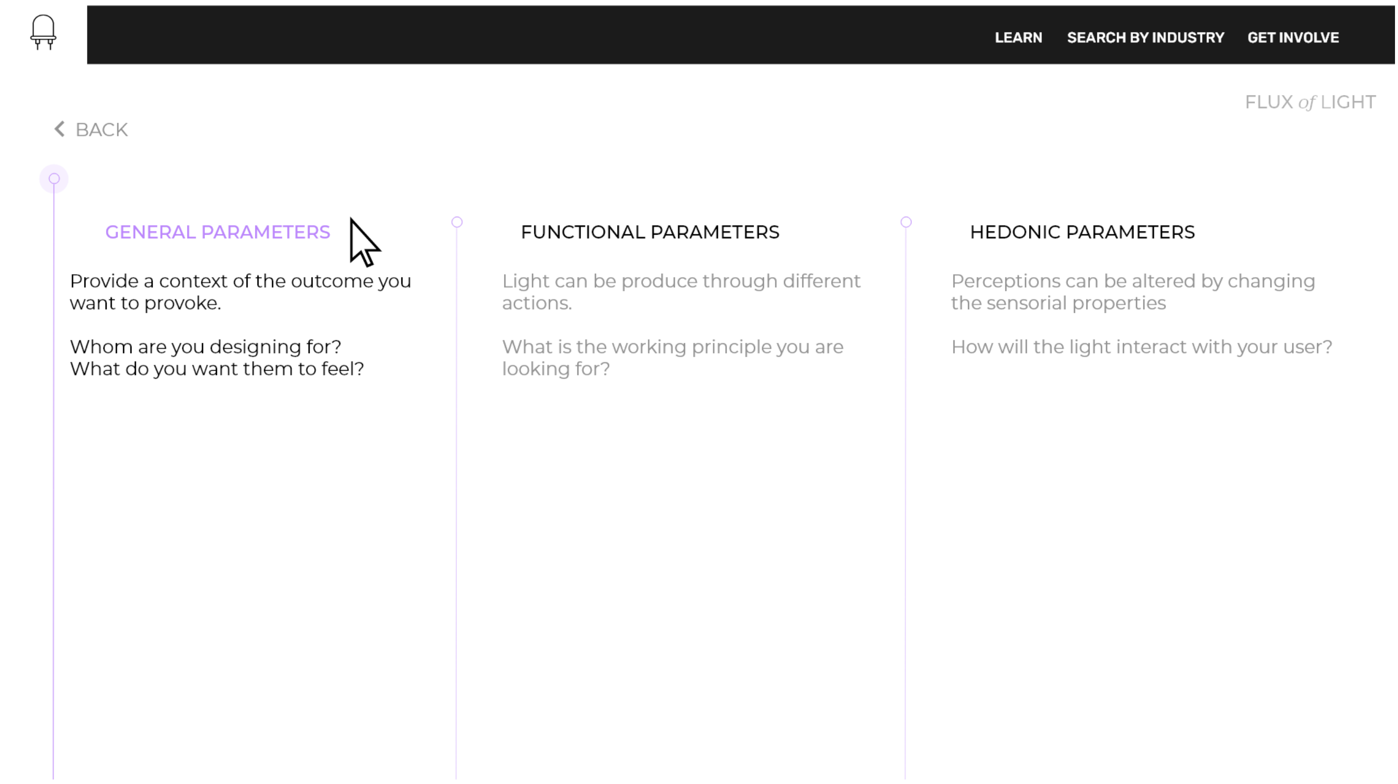


Figure 77. Property search - parameters presentation

Displayed in Figure 79 and 80 is possible to observe the distribution of the general parameters.

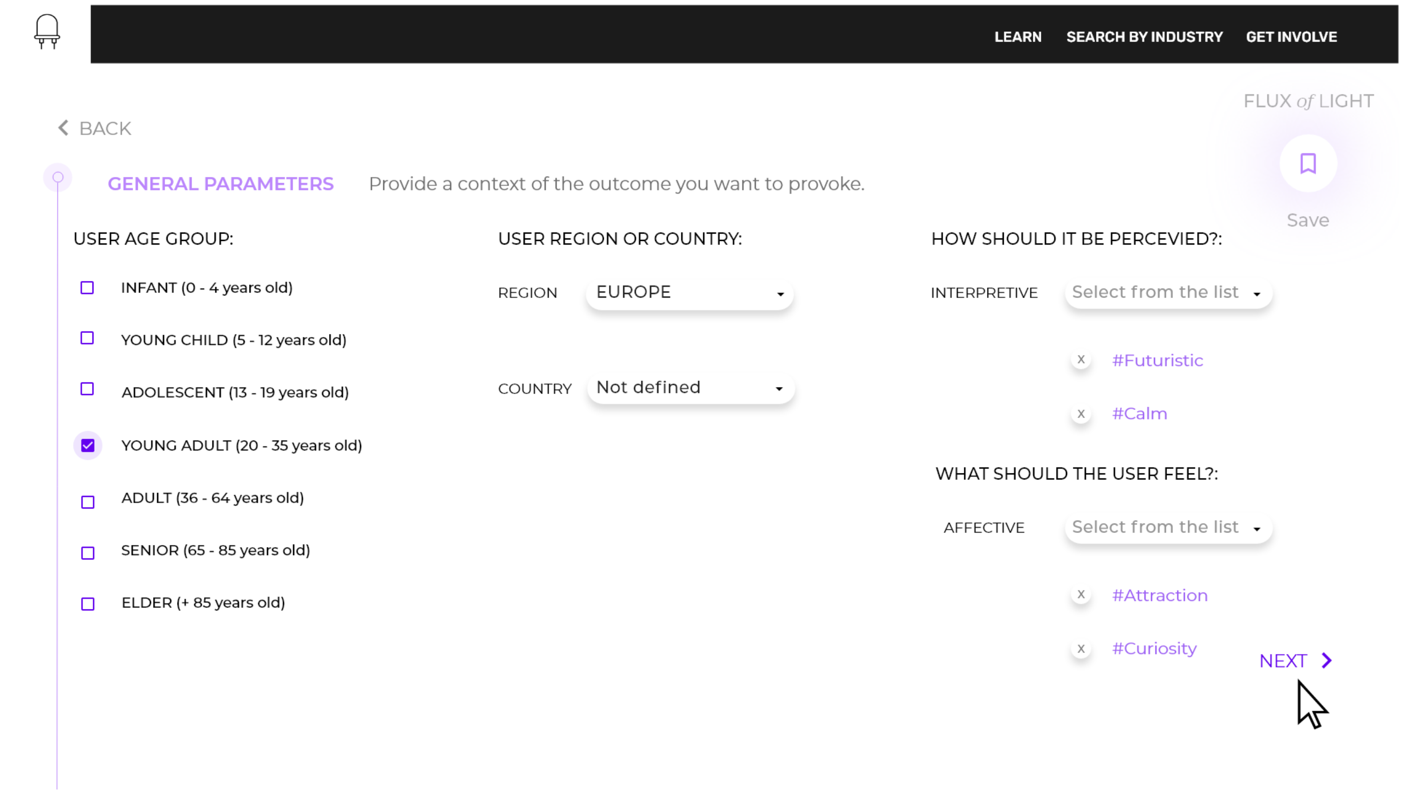


Figure 78. Property search - general parameters screen 1

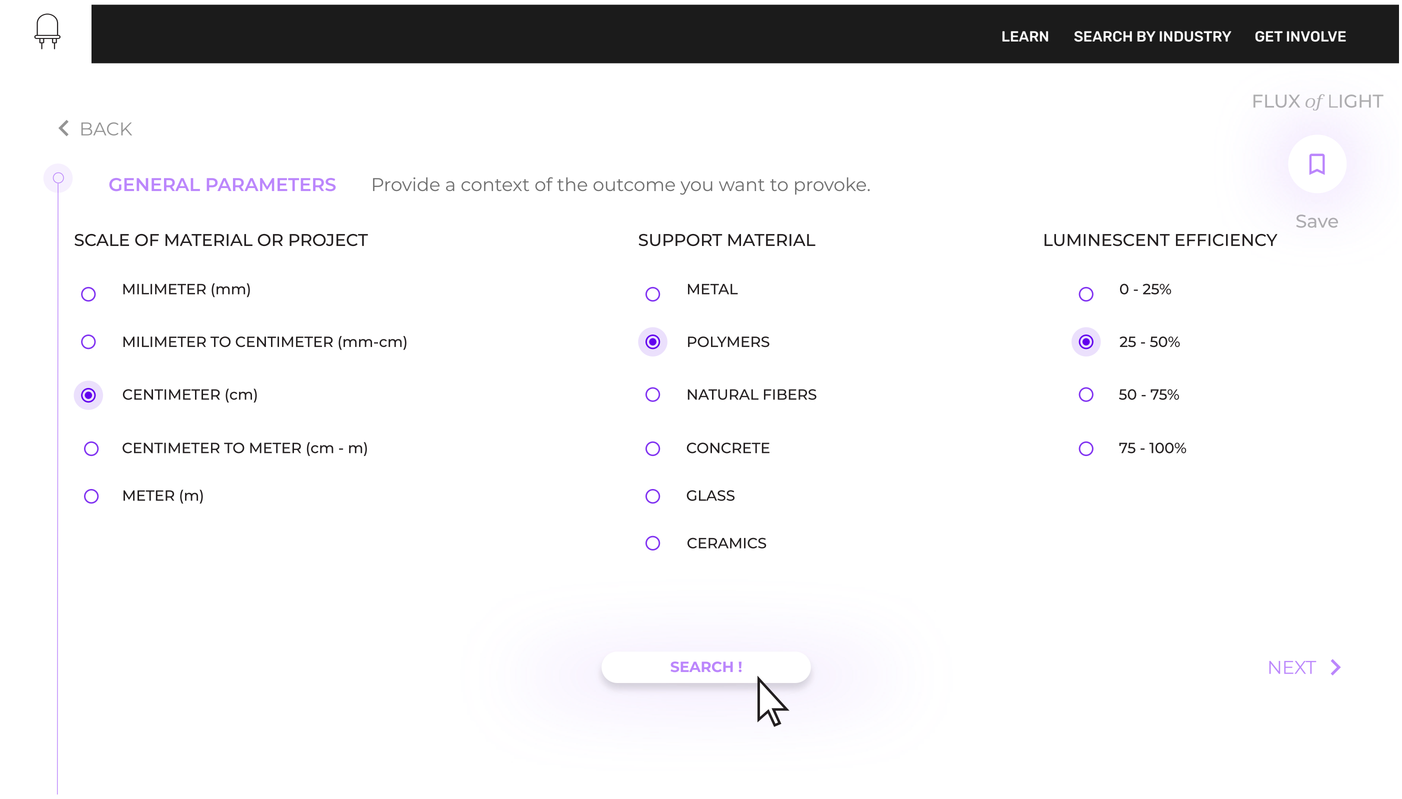


Figure 79. Property search - general parameters screen 2

The property search aims to provide the best-suited material or project according to the luminescent experience the designer aims to provoke.
Nonetheless, to allow flexibility of research, the platform presents a search button to obtain possible solutions at any stage of the evaluation. In the case shown in Figure 80, the possibilities are to select 'Next' and continue with the evaluation of functional parameters and so on, limiting more and more the available options, or to click on 'Search !' right away, obtaining the list of fitted solutions as shown in Figure 81.

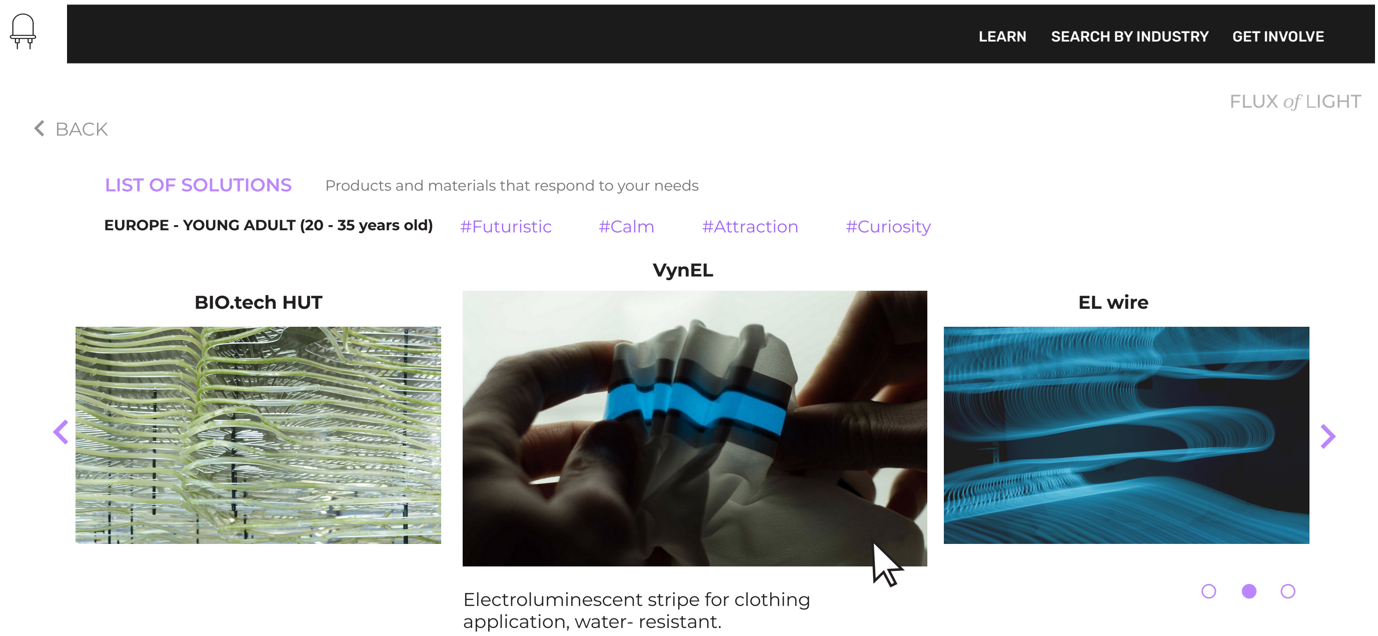


Figure 80. Property search - list of solutions

Finally, an example of a material file is displayed in Figures 82 and 83, according to the selected parameters to be displayed (General, Functional or Hedonic). The material files obtained are the same regardless of the search method.

The files can be saved as favorites for further review, as well as shared with other collaborators.

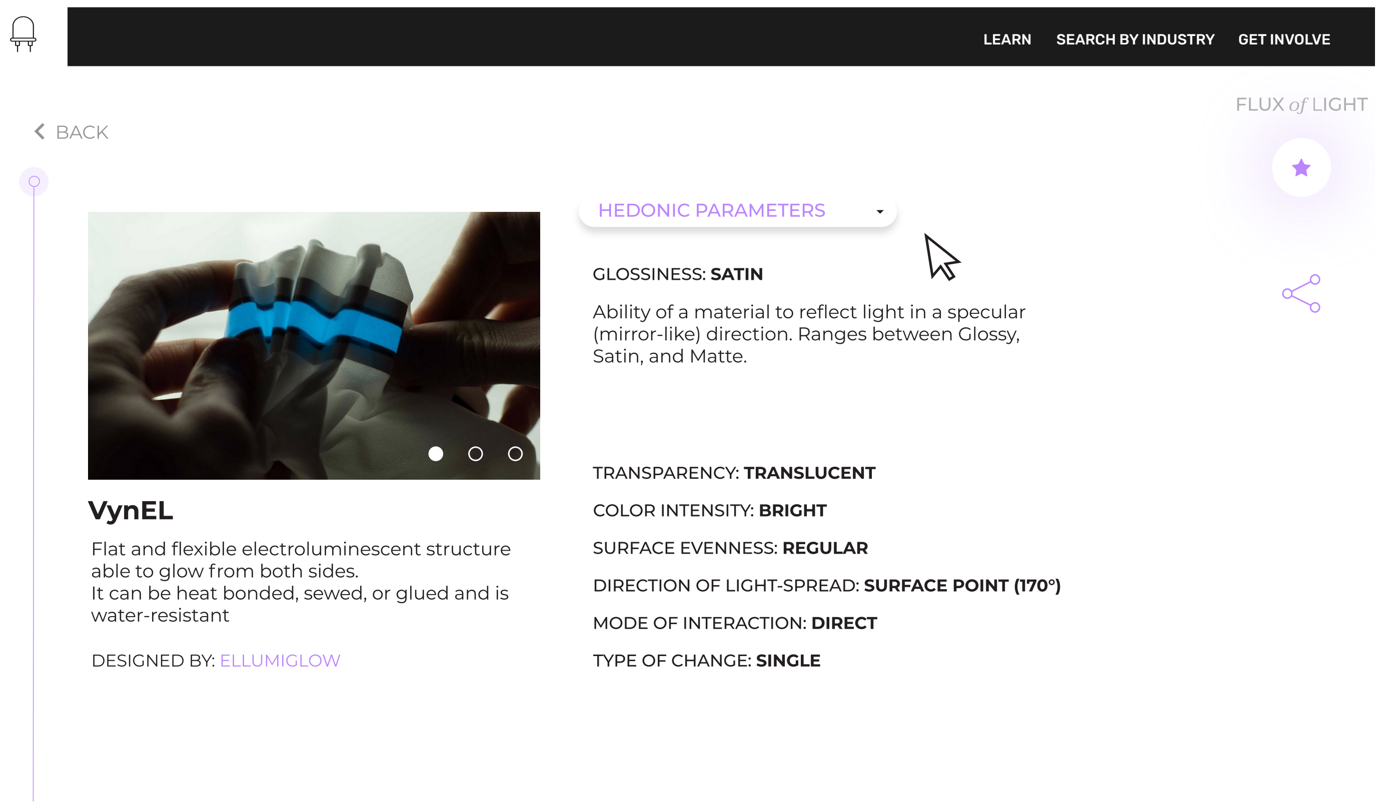


Figure 81. VynEL material file - hedonic parameters

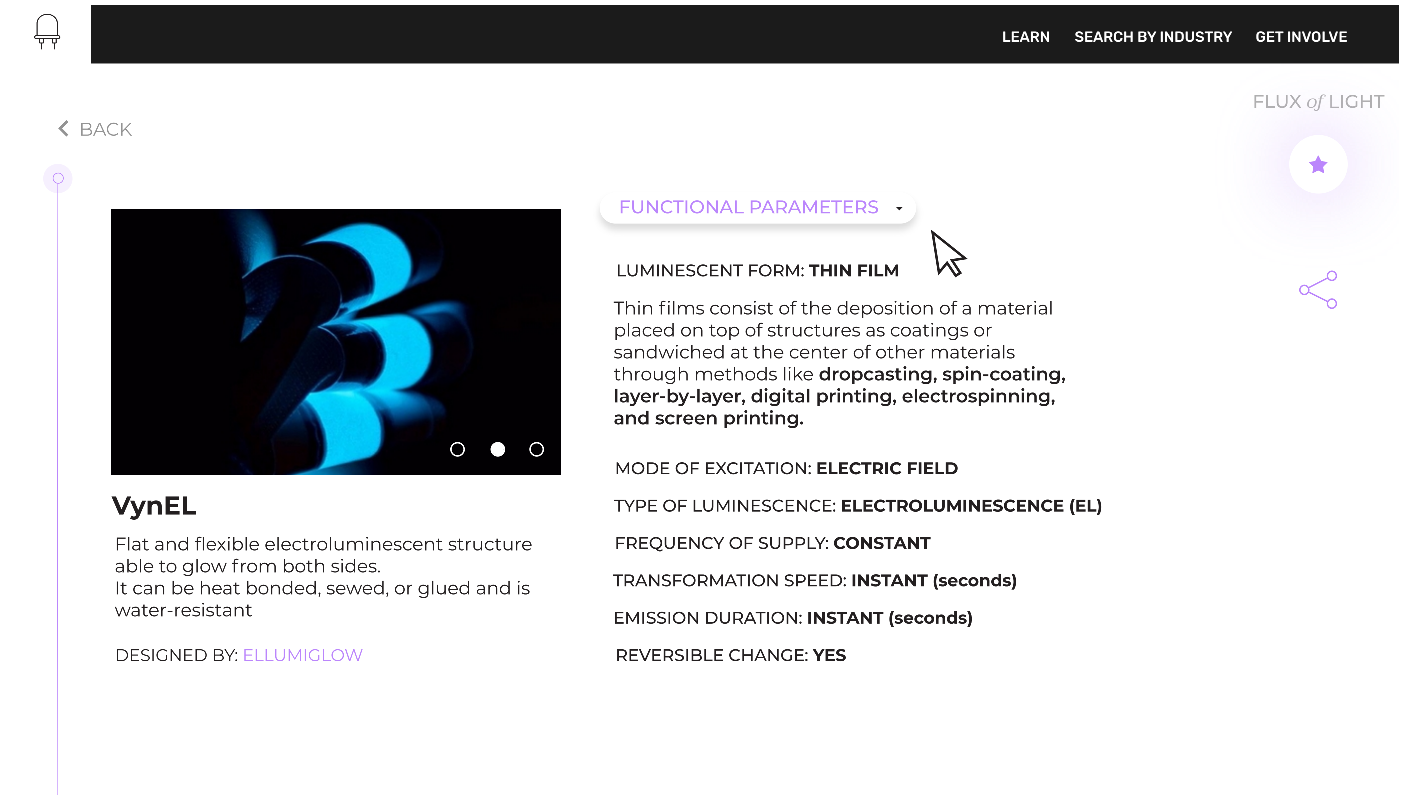


Figure 82. VynEL material file - functional parameters

6.2.2 Search by industry

The search by industry mode is thought of as a fast searcher to foment the built of better products by discovering new materials for specific industries. The possibilities include searching directly for an application or complement with general parameters to guide the solution to a defined experience. The result of search is presented in Figure 85.

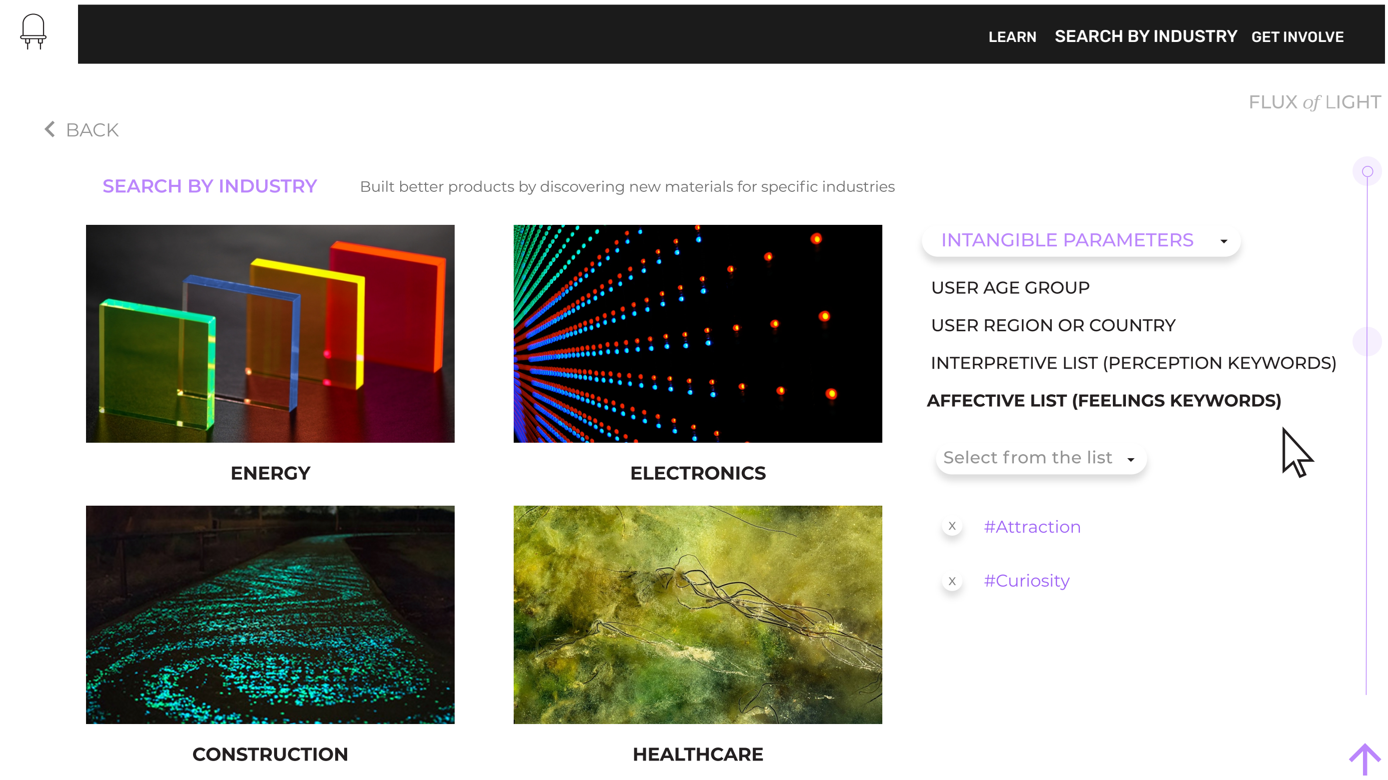


Figure 83. Industry search

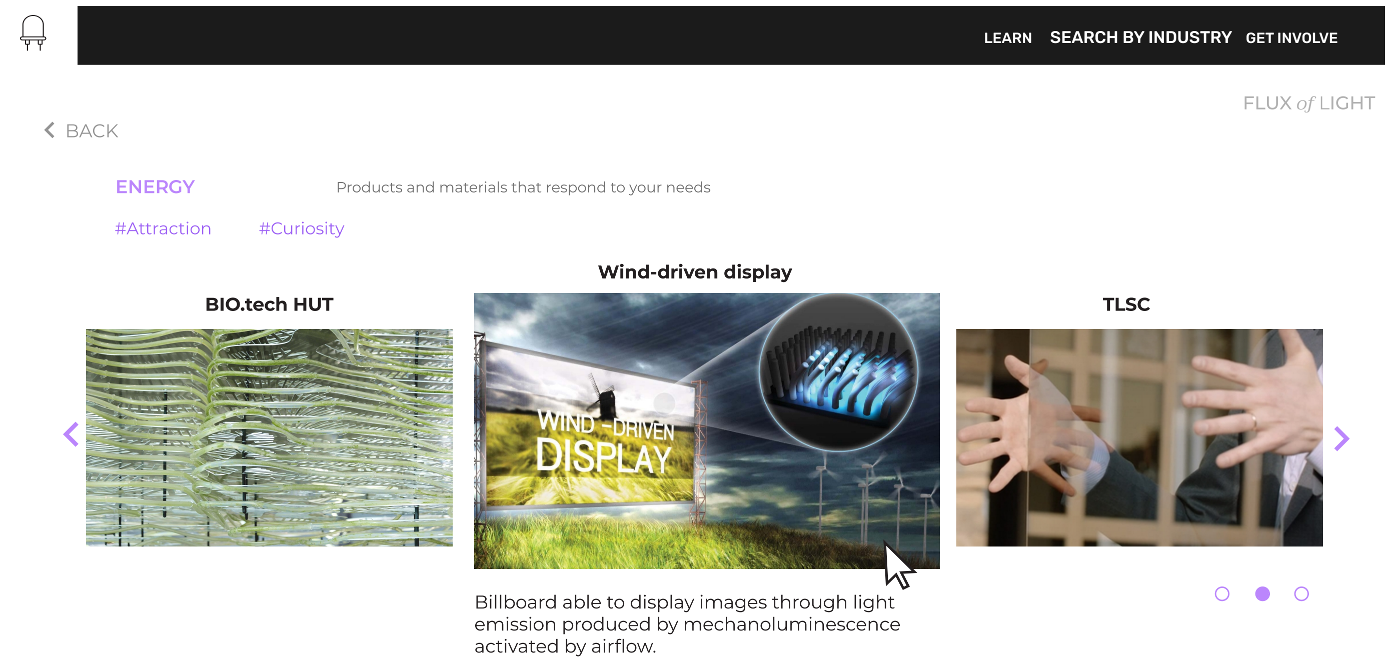


Figure 84. Industry search - list of solutions

6.2.3 Get involve

This particular section is divided into two actions, either to contribute with new luminescent proposals for the database bank of projects or to evaluate projects according to intangible parameters, providing information to feed the data of the internal algorithms of the page to evaluate patterns of responses for defined groups of users. Representation of these options is presented in the following images.

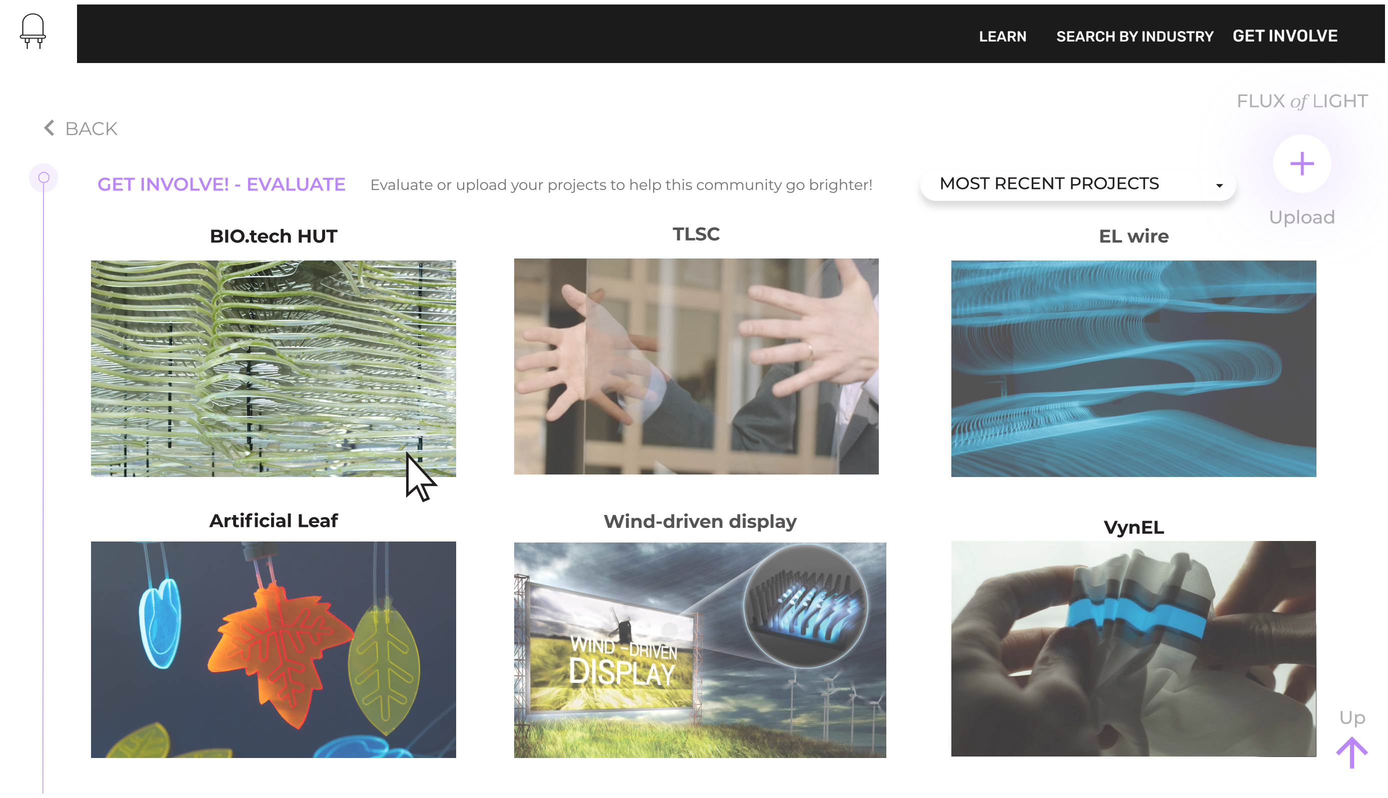


Figure 85. Get involve: Evaluate - selection screen

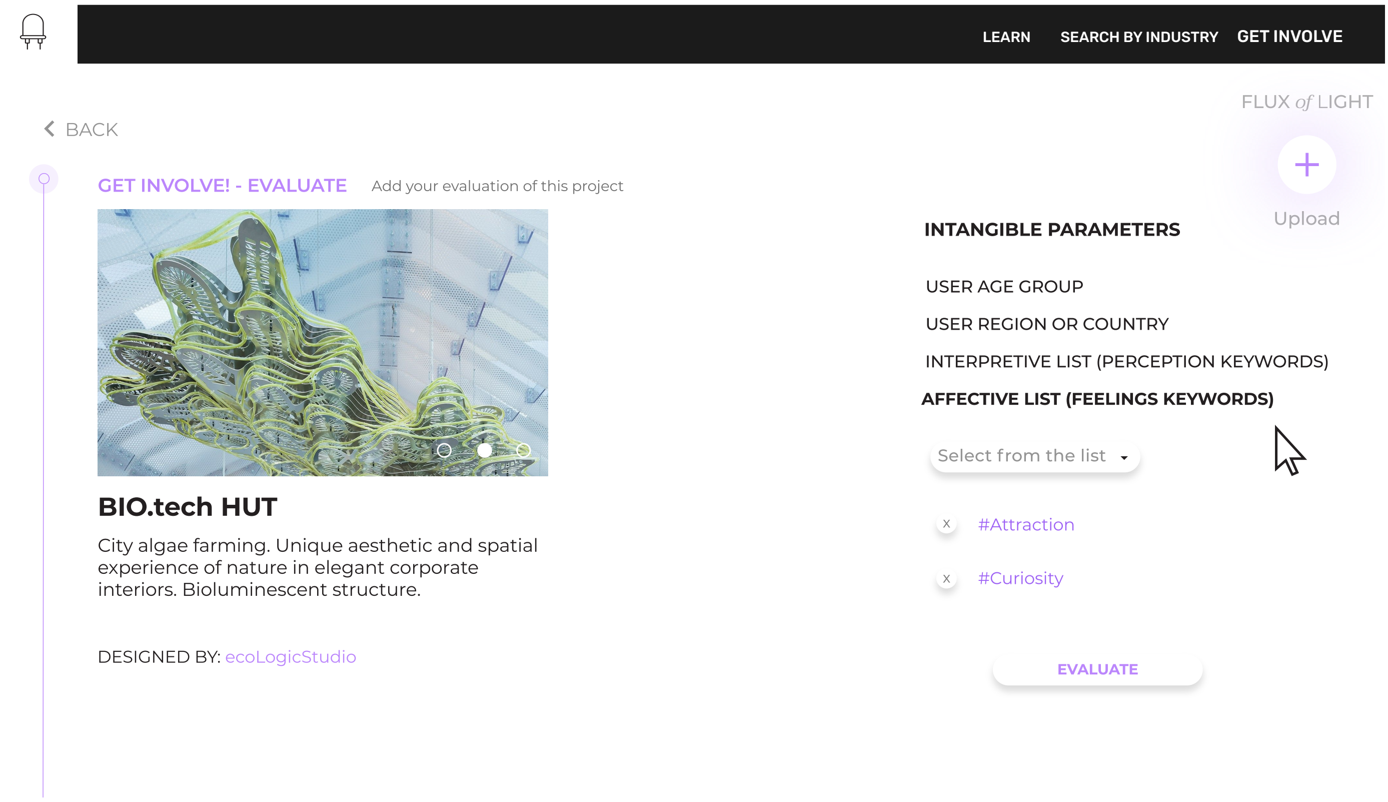


Figure 86. Get involve: Evaluate - intangible parameters screen

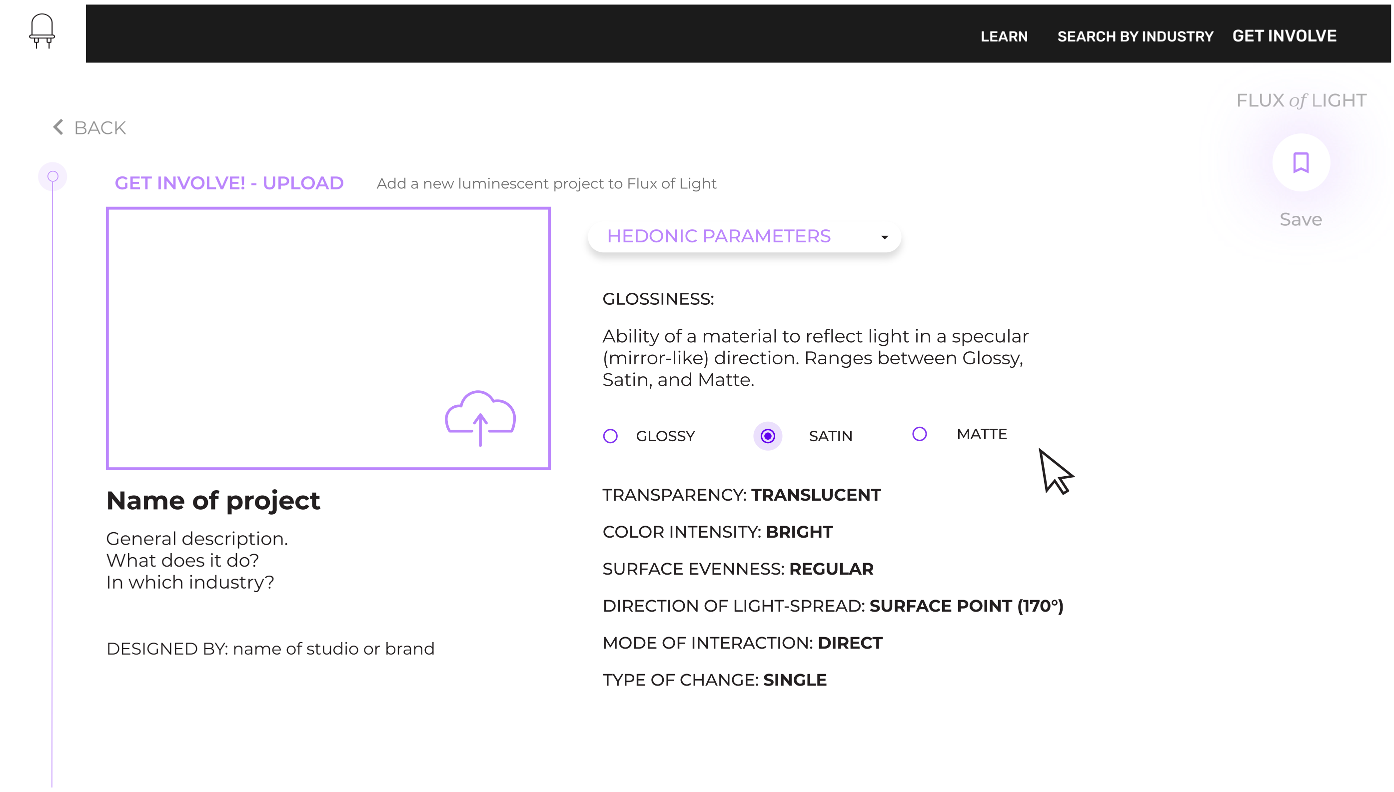


Figure 87. Get involve: Upload

Finally, to upload a new project, Figure 88 presents, ideation of how this process could go, where the user has access to define the different required parameters of the platform.

6.2.4 Learn tab

To contextualize users about luminescent materials, their working principle, as well as the organization and working system of Flux of light, is that they can resolve most of their questions in the 'Learn' tab, where the information is contained for them to review as many times as needed.

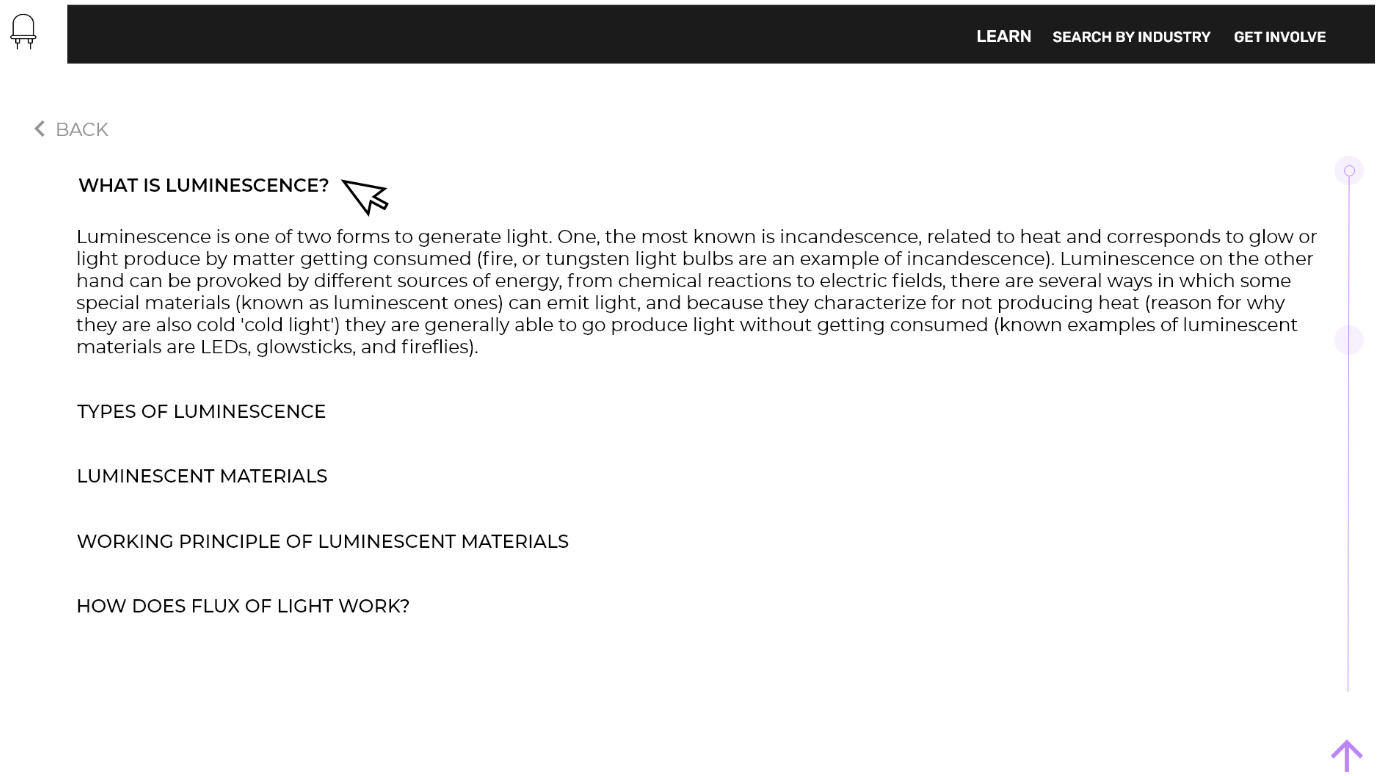
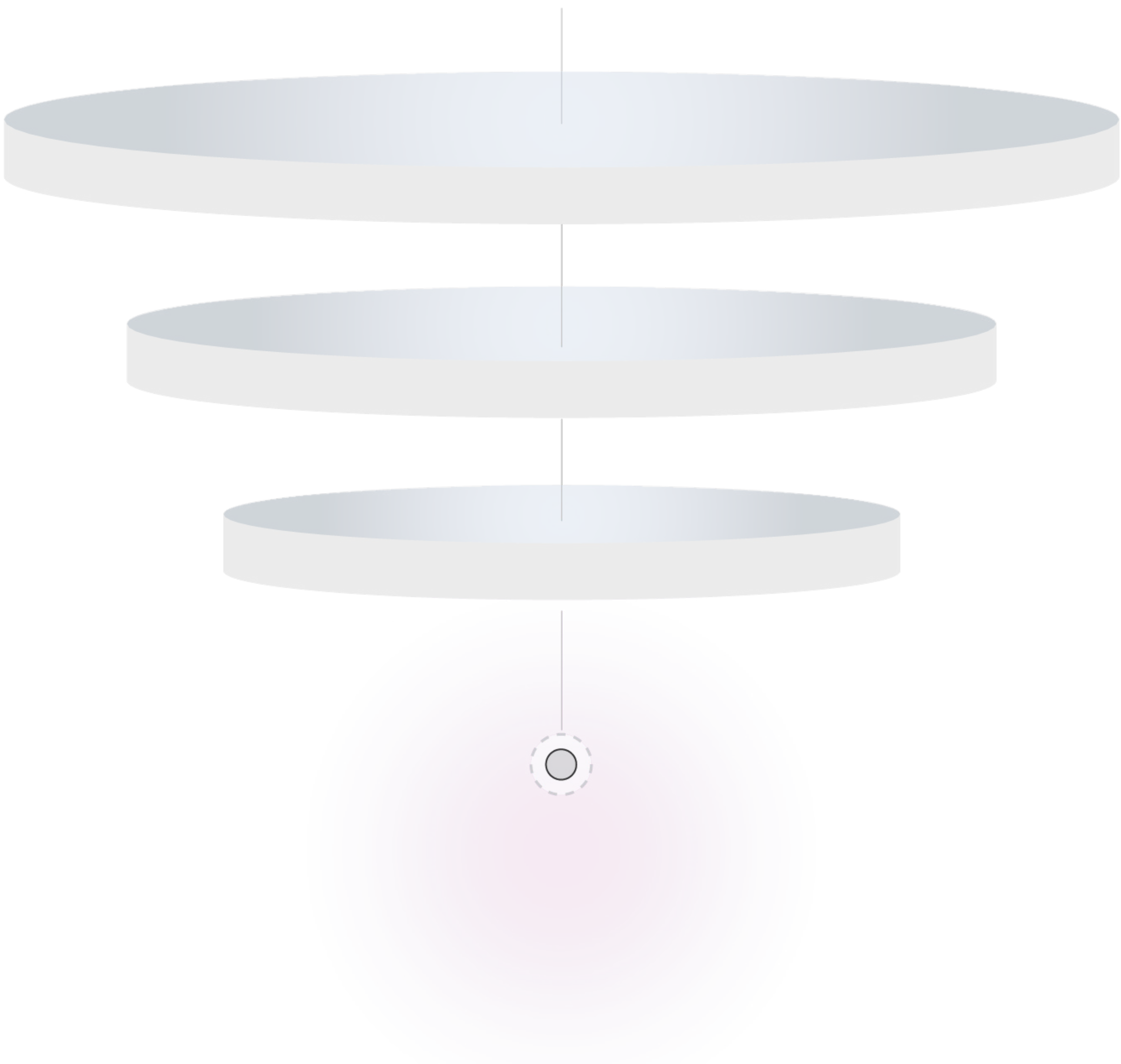


Figure 88. Learn tab

This last image ends the definition of the content and structure of the platform.

Chapter 7:

Mockup, contributions and conclusions



7. Flux of light mockup

Throughout this thesis research, it was possible to observe the evolution and shifts of variables considered in the path of creation in product design. The field is in perpetual questioning of the surroundings, aiming to connect and translate matter to human.
Within the current context, the role of product designers has become enriched as professionals able to direct sensorial dialogues of matter onto others, intentionally eliciting emotions and meaning through functional shapes and colors.

Understanding of the material interaction variables affirms the relevance dynamic materials have over our perception of the world, nonetheless, there is still limited information, and in most cases presented as highly technical or unclear data, regarding Reactive and Proactive materials. For particular cases such as light-emitting luminescent ones, there are even fewer.
But is the recognition of materials able to control the physical phenomenons responsible for our interpretation of the environment, that will construct the future of products.

The field is currently exploring the different layers involved in material selection. Then, the didactics are still evolving into a connection between material and user holistically, providing more complex, and complete interactions.
By comprehending the potentialities that luminescent materials can provide to products, such as luminous efficiency, the versatility of affordance, to name a couple (see Figure 46 for more), together with the impact they have on users demonstrates how essential they are for the development of new concepts and product applications in a variety of industries.
Still, literature review, complemented by the market's offerings and needs shows the lack of tools and support regarding any kind of smart materials in a language that replies to the requirements of students and practitioners of the era.

These gaps of information are taken as an opportunity to study cases and recognize specific parameters that englobe their functionality, and the emotional aspects linked to light-emitting matter. Through these analyses it was possible to propose a norm of relevant information to be considered for the evaluation of them, identifying parameters that allow the selection of characteristics they can present in their physical and temporal form.
Their organization and distribution in an OER platform encourage the smart use and selection of luminescent materials, recognizing their unique properties.

The culmination of this platform, and the studies carried to develop it, is one of the possible solutions available to reply to the curiosity and questioning fostered during my academic years as a product design student, with the hope to provide an instrument that connects materials in their emotional sense with their functional and technical aspects to fellow students and practitioners.

Flux of light proposes a space for exploration, communication, and connection for users to know and questions the pillars that define luminescent materials. The platform serves as a source of inspiration, as well as information, looking for knowledge to grow upon, while laying the foundation for the development of new tools for the recognition of materials of the Reactive and Proactive kind.

The mockup version of the platform can be visited in **this link.**

7.1 Limitations and prospects

Several aspects limited this thesis research, providing space for future upgrades.

First and most importantly, it was carried under a pandemic reality, without access to a laboratory nor the possibility to have direct contact with physical materials, difficulting the comprehension of them.
Moreover, the matter of luminescent materials is a comprehensive subject with many layers, this thesis covers the aspects that were considered relevant from the point of view of the author, but there are still more to cover, and that hopefully, will be explored and complemented by the collaborative work of others.

In concern with the platform content, even though the evaluated case studies aimed to display a variety of industries and uses for luminescent materials, trying to prioritize finished products, there are still underdeveloped cases, therefore presenting the possibility to have variations in the years to come. This might affect some of the evaluated parameters.

Regarding the final proposal, Flux of Light, the biggest limitation it presents is related to the lack of user validations, which is a primordial step to ensure that both the content and how is distributed provides a positive and clear experience for the targeted users.
There is hope that evaluations of the work can be carried in the future, upgrading it. Related to the previous, there is a need for an economical strategy for the platform to sustain itself, this study must be elaborated.

The prospects are related to the implementation of the functional version of the platform, evaluated and validated by both experts and targeted users to provide the most comprehensive experience.
Options of expanding the database tabs to present additional information regarding luminescent materials, or to connect to other webpages (such as the suppliers of materials, responding to another need of the market) are open issues for future evaluations.

Annex

Online questionnaires

Both questionnaires were developed in the online tool Google questionnaire and sent via social media to product design students and early practitioners of the field.

Material selection analysis

This questionnaire is developed to validate ideations regarding material selection sources and parameters in the design field. Its part of the evaluation proposed to obtain the title of MSc in Design & Engineering at Politecnico di Milano, and is an invitation for your collaboration and engagement. Thank you for your support!

*Obligatorio

CONTEXT & INTENTIONS

I would like to know you a little better, please answer your:

1. Age (years) *

    ____

2. Gender: *

    Marca solo un óvalo.

    ◯ Female
    ◯ Male
    ◯ Other
    ◯ Prefer not to say

3. Nationality *

    ____

4. Location. Currently based in *

    ____

5. Career *

    ____

6. Working area *

7. Years of experience working in your field *

Marca solo un óvalo.

- ⬭ Still studying
- ⬭ 0-2
- ⬭ 2-6
- ⬭ 6-10
- ⬭ 10+

This study is focused in Materials, and their selection when creating a product.

8. How do you approach material selection? *

Marca solo un óvalo.

- ⬭ It's evaluated since the conception of the idea. Concept creation
- ⬭ It's integrated it in between design stages, once the concept is elaborated. Embodiment design
- ⬭ At the final stage, before delivering. Detailed design

9. From the following material categories, with which are you more acquainted? *

Selecciona todos los que correspondan.

- ☐ Inactive materials (Materials that prevail the same when faced with an external energetic stimulus - Traditionals e.g., wood, glass, concrete)
- ☐ Reactive materials (Materials that change in properties or energy when faced with an external energetic stimulus - e.g., chromatic/color-changing materials, luminescent /light-emitting materials)
- ☐ Proactive materials (Materials whose properties are controlled and enhanced by microdevices. Computational composites)

10. Would you like to learn more from any of these materials? *

Selecciona todos los que correspondan.

- [ ] Yes, Inactive materials
- [ ] Yes, Reactive materials
- [ ] Yes, Proactive materials
- [ ] No, I am not interested
- [ ] No, I know enough

11. If Yes, what has stopped you?

Selecciona todos los que correspondan.

- [ ] Lack of time
- [ ] Not useful/accepted in my field of industry
- [ ] Lack of access to information (can't pay fees, subscriptions)
- [ ] I don't know where or how to obtain the information

12. Please rank your preferred sources to support material selection? from preferred (1) to least used (6) *

Marca solo un óvalo por fila.

	1	2	3	4	5	6
Books	◯	◯	◯	◯	◯	◯
Suppliers catalogs	◯	◯	◯	◯	◯	◯
Fairs/seminars	◯	◯	◯	◯	◯	◯
Software (CES or other)	◯	◯	◯	◯	◯	◯
Online platforms (MaterialDistrict, Matmatch, Materiom, MaterialConnexion, other)	◯	◯	◯	◯	◯	◯
External consultancy	◯	◯	◯	◯	◯	◯

13. Are you satisfied with the available resources for material selection? *

Marca solo un óvalo.

◯ Yes

◯ No

14. From the following, which ones would you like to access when selecting materials? Please ranl from most relevant (1) to least relevant (11) *

Marca solo un óvalo por fila.

	1	2	3	4	5	6	7	8	9
Inactive materials	◯	◯	◯	◯	◯	◯	◯	◯	◯
Inactive, Reactive and Proactive materials	◯	◯	◯	◯	◯	◯	◯	◯	◯
Finished products	◯	◯	◯	◯	◯	◯	◯	◯	◯
Processes	◯	◯	◯	◯	◯	◯	◯	◯	◯
Suppliers (With availability by location)	◯	◯	◯	◯	◯	◯	◯	◯	◯
Lesgilations and regulations (According to area or material)	◯	◯	◯	◯	◯	◯	◯	◯	◯
Trends (Most popular searches in the platform)	◯	◯	◯	◯	◯	◯	◯	◯	◯
Researches (Articles, tests, and tryouts of/ on materials)	◯	◯	◯	◯	◯	◯	◯	◯	◯
Consultancies (Online specialist feedback)	◯	◯	◯	◯	◯	◯	◯	◯	◯
Reviews (On materials, processes,	◯	◯	◯	◯	◯	◯	◯	◯	◯
Events (Meetings on materials selection)	◯	◯	◯	◯	◯	◯	◯	◯	◯

15. Another not mentioned above. Please describe

16. Please rank the given materials aspects, from preferred (1) to least used (6), according to their importance in your materials selection process: *

Marca solo un óvalo por fila.

	1	2	3	4	5	6
Technical properties (density, conductivity, strength.. .)	⬭	⬭	⬭	⬭	⬭	⬭
Manufacturing requirements (batch size, pieces per hour, etc)	⬭	⬭	⬭	⬭	⬭	⬭
Economic properties (cost for material and production, availability.. .)	⬭	⬭	⬭	⬭	⬭	⬭
Ecological properties (durability, recyclability, sustainability.. .)	⬭	⬭	⬭	⬭	⬭	⬭
Sensorial properties (color, texture, smell.. .)	⬭	⬭	⬭	⬭	⬭	⬭
Intangible properties (emotions, meanings, effects of cultural differences, trends...)	⬭	⬭	⬭	⬭	⬭	⬭

17. Please rank the given materials aspects (from 1 to 6) the ones you manage more (1) to the ones you manage the less (6) *

Marca solo un óvalo por fila.

	1	2	3	4	5	6
Technical properties	⬭	⬭	⬭	⬭	⬭	⬭
Manufacturing requirements	⬭	⬭	⬭	⬭	⬭	⬭
Economic properties	⬭	⬭	⬭	⬭	⬭	⬭
Ecological properties	⬭	⬭	⬭	⬭	⬭	⬭
Sensorial properties	⬭	⬭	⬭	⬭	⬭	⬭
Intangible properties	⬭	⬭	⬭	⬭	⬭	⬭

18. Are there any of these properties that you don't integrate into your design? which one(s)? *

Marca solo un óvalo.

- ⬭ Technical properties
- ⬭ Manufacturing requirements
- ⬭ Economic properties
- ⬭ Ecological properties
- ⬭ Sensorial properties
- ⬭ Intangible properties

19. Why don't you integrate them? *

20. Would you like to share any insight regarding the topic? *

Flux of light: Intangible analysis

The following questionnaire aims to retrieve data regarding the perception of product design students and early practitioners of the field in concern of luminescent materials.

Luminescent materials are smart materials able to emit light when stimulated by some form of energy (e.g. lightstick bracelets, which produce light once the chemical reaction is activated by the mix of the liquids contained inside the bracelet).

Up next, six cards containing different luminescent projects are presented.
Each of the cards displays a short description, accompanied by properties to help define the project and allow the reader a better understanding.

Underneath the cards, two lists with several adjectives are displayed. You are asked to select a maximum of 4 keywords per each of the lists for each of the six projects. By doing so, you will be helping to define them under what is known as intangible aspects.

The collected data is anonymous, for internal use only, and will be processed to contribute to help with the building of 'Flux of light' the result of a proposal presented to obtain the title of MSc in D&E at Politecnico di Milano.

Estimated time to answer: 7 minutes

* Required

Skip to question 1Skip to question 1

About you

Please state the following information

1. Nationality *

2. What is your age group? *

Mark only one oval.

- Under 18 years
- 18 - 24 years
- 25 - 29 years
- 30 - 34 years
- 35 - 39 years

3. Gender *

Mark only one oval.

- Female
- Male
- Prefer not to say

4. Location. Currently based in *

____

5. Are you acquainted with luminescent materials?

Mark only one oval.

- Yes *Skip to question 6*
- No *Skip to section 3 (Luminescent materials)*

Luminescent materials

Luminescent materials are materials able to emit light when stimulated by some form of energy (e.g. lightstick bracelets, which produce light once the chemical reaction is activated by the mix of the liquids contained inside the bracelet). They are considered smart as they would seem to "respond", creating a complex interaction with the user. Other known examples of luminescent materials are glow in the dark paint and LED lights.

Keyword selection - 1

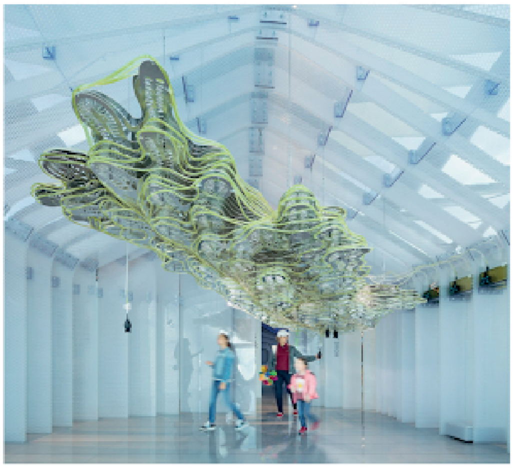
Up next, six cards containing different luminescent projects are presented. Underneath the cards, two lists with several adjectives are displayed. You are asked to select a maximum of 4 keywords per each of the lists for each of the six projects. The keywords should reflect how you perceive the projects.

6. 1. BIO.tech HUT - Interpretive level *

Please select a maximum of four keywords that reflect how you perceive this project

BIO.tech HUT

City algae farming. Unique aesthetic and spatial experience of nature in elegant corporate interiors



Luminous efficiency: Unknown

Functional aspects	
Parameter	**Response**
Mode of excitation	Biochemical reaction
Frequency of supply	Intermittent
Transformation speed	Long-delayed (minutes-hours)
Emission duration	Long-delayed decay (minutes-hours)
Reversible change	Yes
Luminescent form	Bio-organism

Hedonic aspects	
Parameter	**Response**
Glossiness	Satin
Transparency	Opaque
Color intensity	Bright
Surface eveness	Irregular
Type of change (S/C/M)	Single
Direction of light-spread	All around (360°)

Check all that apply.

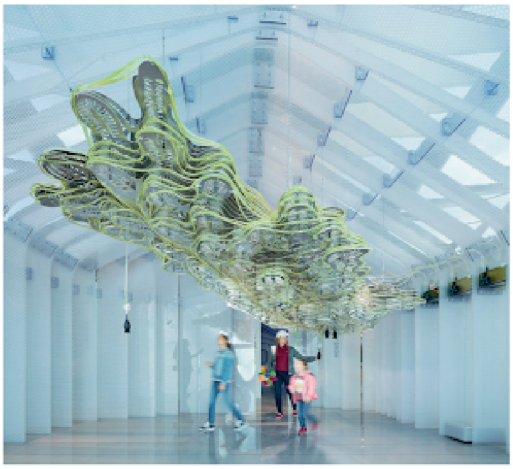
- [ ] Aggressive
- [ ] Calm
- [ ] Cozy
- [ ] Aloof
- [ ] Elegant
- [ ] Vulgar
- [ ] Frivolous
- [ ] Sober
- [ ] Futuristic
- [ ] Nostalgic
- [ ] Masculine
- [ ] Feminine
- [ ] Ordinary
- [ ] Strange
- [ ] Sexy
- [ ] Not sexy
- [ ] Toy-like
- [ ] Professional
- [ ] Natural
- [ ] Unnatural
- [ ] Hand-crafted
- [ ] Manufactured

7. 1. BIO.tech HUT - Affective level *

Please select a maximum of four keywords that reflect how you perceive this project

BIO.tech HUT

City algae farming. Unique aesthetic and spatial experience of nature in elegant corporate interiors



Luminous efficiency: Unknown

Functional aspects	
Parameter	**Response**
Mode of excitation	Biochemical reaction
Frequency of supply	Intermittent
Transformation speed	Long-delayed (minutes-hours)
Emission duration	Long-delayed decay (minutes-hours)
Reversible change	Yes
Luminescent form	Bio-organism

Hedonic aspects	
Parameter	**Response**
Glossiness	Satin
Transparency	Opaque
Color intensity	Bright
Surface eveness	Irregular
Type of change (S/C/M)	Single
Direction of light-spread	All around (360°)

Check all that apply.

- [ ] Love
- [ ] Frustation
- [ ] Amusement
- [ ] Boredom
- [ ] Surprise
- [ ] Disappointment
- [ ] Confidence
- [ ] Reluctance
- [ ] Enchantment
- [ ] Confusion
- [ ] Respect
- [ ] Rejection
- [ ] Attraction
- [ ] Disgust
- [ ] Curiosity
- [ ] Melancholy
- [ ] Fascination
- [ ] Distrust
- [ ] Comfort
- [ ] Doubt

8. 2. Light-Emitting Cement - Interpretive level *

Please select a maximum of four keywords that reflect how you perceive this project

Light Emitting Cement

Self-luminescent cement-based composite materials (SLCCM) for environmental protection, smart pavement

Luminous efficiency: Unknown

Functional aspects	
Parameter	**Response**
Mode of excitation	Absorption of light
Frequency of supply	Intermittent
Transformation speed	Delayed (seconds - minutes)
Emission duration	Long-delayed decay (minutes-hours)
Reversible change	Yes
Luminescent form	Powder

Hedonic aspects	
Parameter	**Response**
Glossiness	Matte
Transparency	Opaque
Color intensity	Bright
Surface eveness	Irregular
Type of change (S/C/M)	Single
Direction of light-spread	Surface source (170°)

Check all that apply.

- [ ] Aggressive
- [ ] Calm
- [ ] Cozy
- [ ] Aloof
- [ ] Elegant
- [ ] Vulgar
- [ ] Frivolous
- [ ] Sober
- [ ] Futuristic
- [ ] Nostalgic
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- [ ] Ordinary
- [ ] Strange
- [ ] Sexy
- [ ] Not sexy
- [ ] Toy-like
- [ ] Professional
- [ ] Natural
- [ ] Unnatural
- [ ] Hand-crafted
- [ ] Manufactured

9. 2. Light-Emitting Cement - Affective level *

Please select a maximum of four keywords that reflect how you perceive this project

Light Emitting Cement

Self-luminescent cement-based composite materials (SLCCM) for environmental protection, smart pavement

Luminous efficiency: Unknown

Functional aspects	
Parameter	**Response**
Mode of excitation	Absorption of light
Frequency of supply	Intermittent
Transformation speed	Delayed (seconds - minutes)
Emission duration	Long-delayed decay (minutes-hours)
Reversible change	Yes
Luminescent form	Powder

Hedonic aspects	
Parameter	**Response**
Glossiness	Matte
Transparency	Opaque
Color intensity	Bright
Surface eveness	Irregular
Type of change (S/C/M)	Single
Direction of light-spread	Surface source (170°)

Check all that apply.

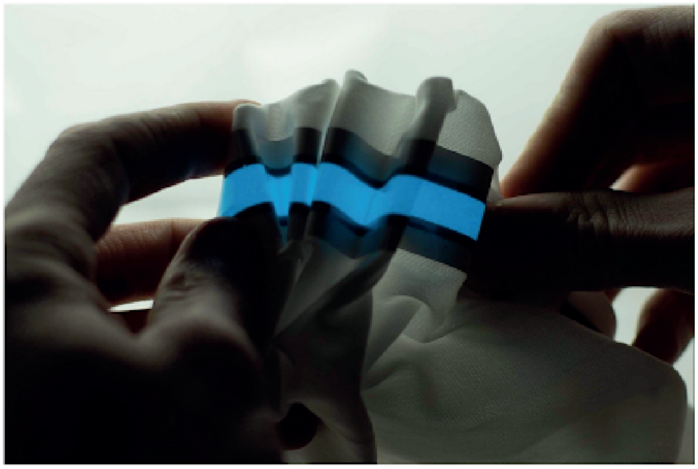
- [ ] Love
- [ ] Frustation
- [ ] Amusement
- [ ] Boredom
- [ ] Surprise
- [ ] Disappointment
- [ ] Confidence
- [ ] Reluctance
- [ ] Enchantment
- [ ] Confusion
- [ ] Respect
- [ ] Rejection
- [ ] Attraction
- [ ] Disgust
- [ ] Curiosity
- [ ] Melancholy
- [ ] Fascination
- [ ] Distrust
- [ ] Comfort
- [ ] Doubt

10. 3. VynEL - Interpretive level *

Please select a maximum of four keywords that reflect how you perceive this project

VynEL

Flat and flexible structure able to glow from both sides. It can be heat bonded, sewed, or glued. Water-resistant



Luminous efficiency: Unknown

Functional aspects	
Parameter	**Response**
Mode of excitation	Electric field
Frequency of supply	Constant
Transformation speed	Instant (seconds)
Emission duration	Instant decay (seconds)
Reversible change	Yes
Luminescent form	Thin film

Hedonic aspects	
Parameter	**Response**
Glossiness	Satin
Transparency	Translucent
Color intensity	Bright
Surface eveness	Regular
Type of change (S/C/M)	Single
Direction of light-spread	Surface source (170°)

Check all that apply.

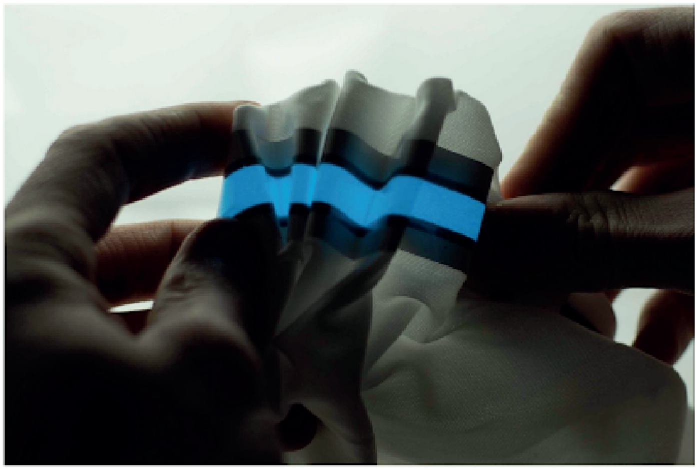
- [ ] Aggressive
- [ ] Calm
- [ ] Cozy
- [ ] Aloof
- [ ] Elegant
- [ ] Vulgar
- [ ] Frivolous
- [ ] Sober
- [ ] Futuristic
- [ ] Nostalgic
- [ ] Masculine
- [ ] Feminine
- [ ] Ordinary
- [ ] Strange
- [ ] Sexy
- [ ] Not sexy
- [ ] Toy-like
- [ ] Professional
- [ ] Natural
- [ ] Unnatural
- [ ] Hand-crafted
- [ ] Manufactured

11. 3. VynEL - Affective level *

Please select a maximum of four keywords that reflect how you perceive this project

VynEL

Flat and flexible structure able to glow from both sides. It can be heat bonded, sewed, or glued. Water-resistant



Luminous efficiency: Unknown

Functional aspects	
Parameter	**Response**
Mode of excitation	Electric field
Frequency of supply	Constant
Transformation speed	Instant (seconds)
Emission duration	Instant decay (seconds)
Reversible change	Yes
Luminescent form	Thin film

Hedonic aspects	
Parameter	**Response**
Glossiness	Satin
Transparency	Translucent
Color intensity	Bright
Surface eveness	Regular
Type of change (S/C/M)	Single
Direction of light-spread	Surface source (170°)

Check all that apply.

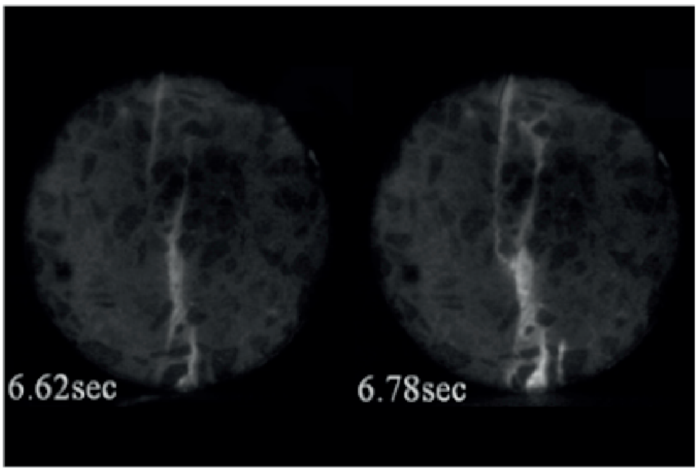
- [ ] Love
- [ ] Frustation
- [ ] Amusement
- [ ] Boredom
- [ ] Surprise
- [ ] Disappointment
- [ ] Confidence
- [ ] Reluctance
- [ ] Enchantment
- [ ] Confusion
- [ ] Respect
- [ ] Rejection
- [ ] Attraction
- [ ] Disgust
- [ ] Curiosity
- [ ] Melancholy
- [ ] Fascination
- [ ] Distrust
- [ ] Comfort
- [ ] Doubt

12. **4. ML paint - Interpretive level** *

Please select a maximum of four keywords that reflect how you perceive this project

ML paint

Paint for the visualization of crack propagation mechanisms in concrete structures



Luminous efficiency: Unknown

Functional aspects	
Parameter	**Response**
Mode of excitation	Frictional forces
Frequency of supply	Intermittent
Transformation speed	Instant (seconds)
Emission duration	Delayed decay (seconds - minutes)
Reversible change	No
Luminescent form	Liquids & gels

Hedonic aspects	
Parameter	**Response**
Glossiness	Matte
Transparency	Translucent
Color intensity	Dim
Surface eveness	Regular
Type of change (S/C/M)	Single
Direction of light-spread	Surface source (170°)

Check all that apply.

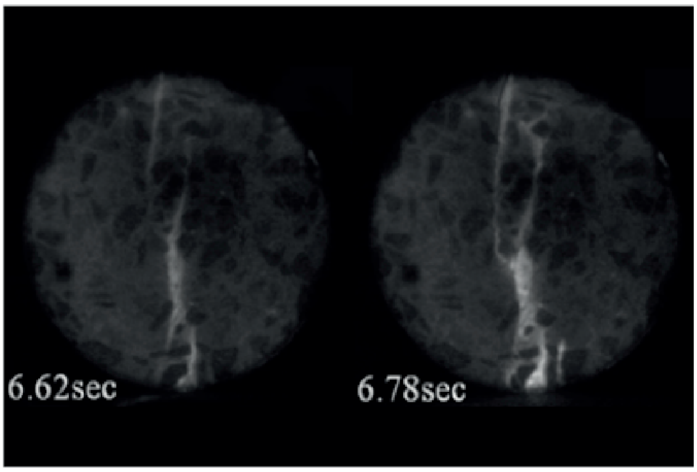
- [ ] Aggressive
- [ ] Calm
- [ ] Cozy
- [ ] Aloof
- [ ] Elegant
- [ ] Vulgar
- [ ] Frivolous
- [ ] Sober
- [ ] Futuristic
- [ ] Nostalgic
- [ ] Masculine
- [ ] Feminine
- [ ] Ordinary
- [ ] Strange
- [ ] Sexy
- [ ] Not sexy
- [ ] Toy-like
- [ ] Professional
- [ ] Natural
- [ ] Unnatural
- [ ] Hand-crafted
- [ ] Manufactured

13. 4. ML paint - Affective level *

Please select a maximum of four keywords that reflect how you perceive this project

ML paint

Paint for the visualization of crack propagation mechanisms in concrete structures



Luminous efficiency: Unknown

Functional aspects	
Parameter	**Response**
Mode of excitation	Frictional forces
Frequency of supply	Intermittent
Transformation speed	Instant (seconds)
Emission duration	Delayed decay (seconds - minutes)
Reversible change	No
Luminescent form	Liquids & gels

Hedonic aspects	
Parameter	**Response**
Glossiness	Matte
Transparency	Translucent
Color intensity	Dim
Surface eveness	Regular
Type of change (S/C/M)	Single
Direction of light-spread	Surface source (170°)

Check all that apply.

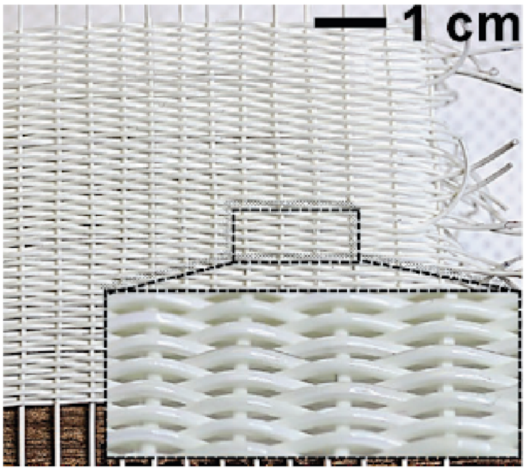
- [ ] Love
- [ ] Frustation
- [ ] Amusement
- [ ] Boredom
- [ ] Surprise
- [ ] Disappointment
- [ ] Confidence
- [ ] Reluctance
- [ ] Enchantment
- [ ] Confusion
- [ ] Respect
- [ ] Rejection
- [ ] Attraction
- [ ] Disgust
- [ ] Curiosity
- [ ] Melancholy
- [ ] Fascination
- [ ] Distrust
- [ ] Comfort
- [ ] Doubt

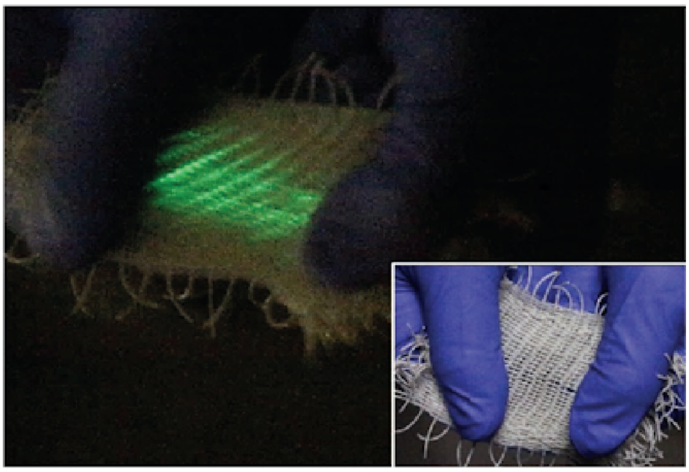
14. 5. ML fiber - Interpretive level *

Please select a maximum of four keywords that reflect how you perceive this project

ML fiber

Fiber with symmetrical brightness for wearable electronic textiles





Luminous efficiency: Unknown

Functional aspects	
Parameter	**Response**
Mode of excitation	Frictional forces
Frequency of supply	Intermittent
Transformation speed	Instant (seconds)
Emission duration	Delayed decay (seconds - minutes)
Reversible change	Yes
Luminescent form	Fibers & filaments

Hedonic aspects	
Parameter	**Response**
Glossiness	Matte
Transparency	Opaque
Color intensity	Dim
Surface eveness	Irregular
Type of change (S/C/M)	Single
Direction of light-spread	All around (360°)

Check all that apply.

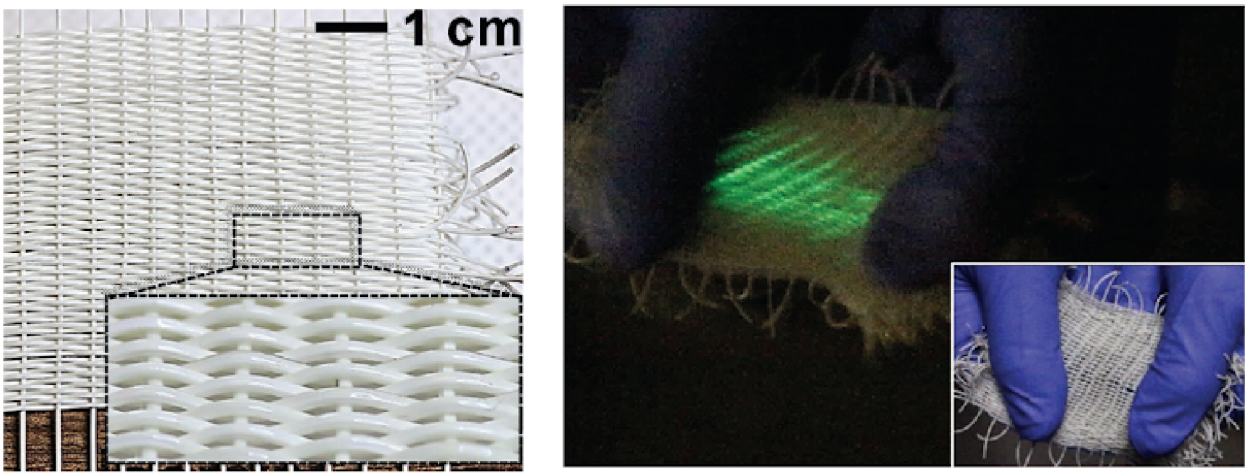
- [ ] Aggressive
- [ ] Calm
- [ ] Cozy
- [ ] Aloof
- [ ] Elegant
- [ ] Vulgar
- [ ] Frivolous
- [ ] Sober
- [ ] Futuristic
- [ ] Nostalgic
- [ ] Masculine
- [ ] Feminine
- [ ] Ordinary
- [ ] Strange
- [ ] Sexy
- [ ] Not sexy
- [ ] Toy-like
- [ ] Professional
- [ ] Natural
- [ ] Unnatural
- [ ] Hand-crafted
- [ ] Manufactured

15. 5. ML fiber - Affective level *

Please select a maximum of four keywords that reflect how you perceive this project

ML fiber

Fiber with symmetrical brightness for wearable electronic textiles



Luminous efficiency: Unknown

Functional aspects	
Parameter	**Response**
Mode of excitation	Frictional forces
Frequency of supply	Intermittent
Transformation speed	Instant (seconds)
Emission duration	Delayed decay (seconds - minutes)
Reversible change	Yes
Luminescent form	Fibers & filaments

Hedonic aspects	
Parameter	**Response**
Glossiness	Matte
Transparency	Opaque
Color intensity	Dim
Surface eveness	Irregular
Type of change (S/C/M)	Single
Direction of light-spread	All around (360°)

Check all that apply.

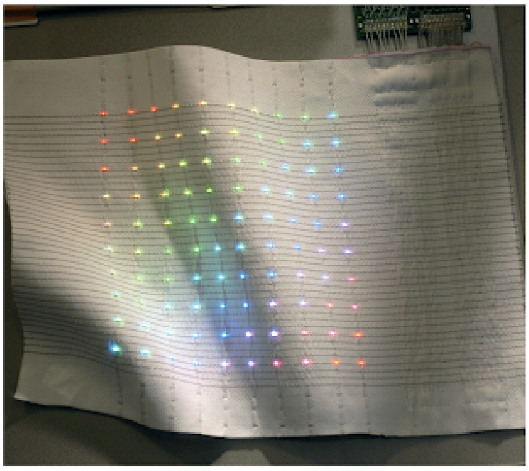
- [ ] Love
- [ ] Frustation
- [ ] Amusement
- [ ] Boredom
- [ ] Surprise
- [ ] Disappointment
- [ ] Confidence
- [ ] Reluctance
- [ ] Enchantment
- [ ] Confusion
- [ ] Respect
- [ ] Rejection
- [ ] Attraction
- [ ] Disgust
- [ ] Curiosity
- [ ] Melancholy
- [ ] Fascination
- [ ] Distrust
- [ ] Comfort
- [ ] Doubt

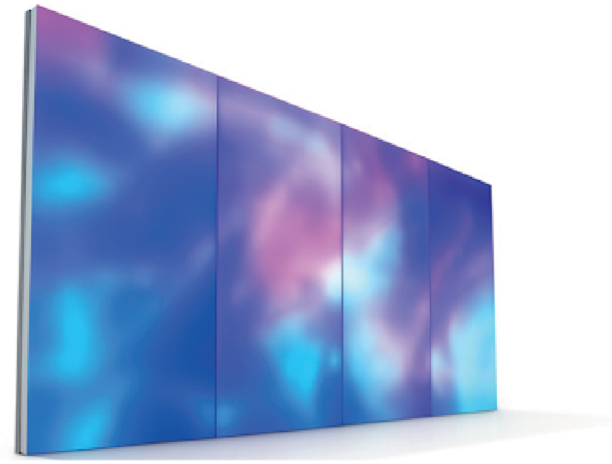
16. 6. Luminous textiles - Interpretive level *

Please select a maximum of four keywords that reflect how you perceive this project

Luminous textiles

Configurable lighting system that integrates multi-colored LEDs seamlessly within beautiful fabric panels





Luminous efficiency: Unknown

Functional aspects	
Parameter	**Response**
Mode of excitation	Electric field
Frequency of supply	Constant
Transformation speed	Instant (seconds)
Emission duration	Instant decay (seconds)
Reversible change	Yes
Luminescent form	Solid-state lighting

Hedonic aspects	
Parameter	**Response**
Glossiness	Satin
Transparency	Opaque
Color intensity	Bright
Surface eveness	Regular
Type of change (S/C/M)	Continuous
Direction of light-spread	Surface source (170°)

Check all that apply.

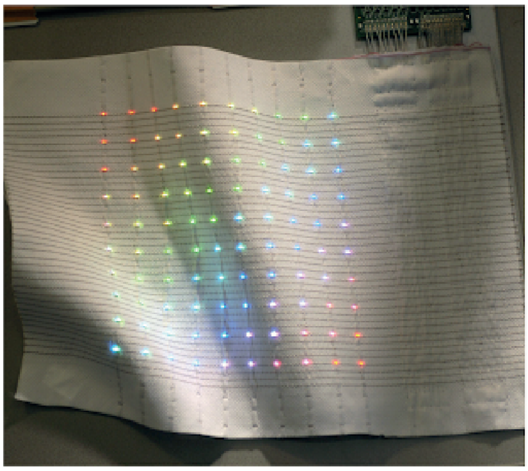
- [ ] Aggressive
- [ ] Calm
- [ ] Cozy
- [ ] Aloof
- [ ] Elegant
- [ ] Vulgar
- [ ] Frivolous
- [ ] Sober
- [ ] Futuristic
- [ ] Nostalgic
- [ ] Masculine
- [ ] Feminine
- [ ] Ordinary
- [ ] Strange
- [ ] Sexy
- [ ] Not sexy
- [ ] Toy-like
- [ ] Professional
- [ ] Natural
- [ ] Unnatural
- [ ] Hand-crafted
- [ ] Manufactured

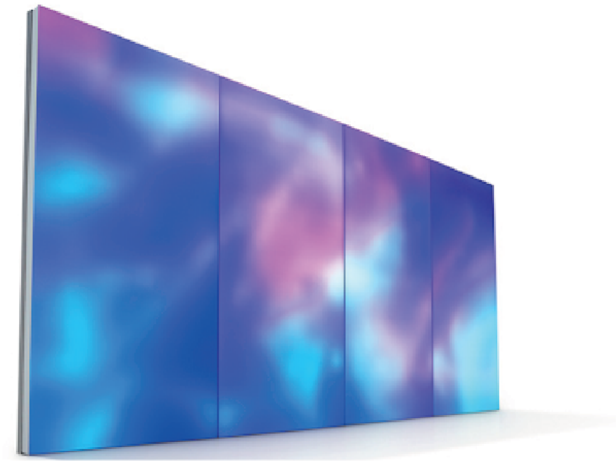
17. 6. Luminous textiles - Affective level *

Please select a maximum of four keywords that reflect how you perceive this project

Luminous textiles

Configurable lighting system that integrates multi-colored LEDs seamlessly within beautiful fabric panels





Luminous efficiency: Unknown

Functional aspects	
Parameter	**Response**
Mode of excitation	Electric field
Frequency of supply	Constant
Transformation speed	Instant (seconds)
Emission duration	Instant decay (seconds)
Reversible change	Yes
Luminescent form	Solid-state lighting

Hedonic aspects	
Parameter	**Response**
Glossiness	Satin
Transparency	Opaque
Color intensity	Bright
Surface eveness	Regular
Type of change (S/C/M)	Continuous
Direction of light-spread	Surface source (170°)

Check all that apply.

- [ ] Love
- [ ] Frustation
- [ ] Amusement
- [ ] Boredom
- [ ] Surprise
- [ ] Disappointment
- [ ] Confidence
- [ ] Reluctance
- [ ] Enchantment
- [ ] Confusion
- [ ] Respect
- [ ] Rejection
- [ ] Attraction
- [ ] Disgust
- [ ] Curiosity
- [ ] Melancholy
- [ ] Fascination
- [ ] Distrust
- [ ] Comfort
- [ ] Doubt

POLITECNICO DI MILANO

School of Design

Master of Science in Design & Engineering

POLITECNICO
MILANO 1863

Flux of light

Development of framework for OER Platform to Support and Guide the Incorporation of Luminescent Materials in the Product Design Field

Supervisor: Prof. Barbara Del Curto

Co-Supervisors: Flavia Papile, Andrea Marinelli

Author: Laura Palma Marambio

Student N° 913214

Academic year 2019/2020